GLOBAL ENERGY MODELLING: A BIOPHYSICAL APPROACH (GEMBA)

A thesis submitted in partial fulfilment of the

requirements for the Degree of

Doctor of Philosophy in Mechanical Engineering

In

the University of Canterbury

by

Michael Anthony Joseph Dale

University of Canterbury

2010

TABLE OF CONTENTS

TABLE OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

The completion of this PhD project has been an exciting process of both academic exploration as well as self-discovery which would not have been possible without the continued(ing) support of some incredible people; some of whom were known to me already and others that I have been lucky enough to meet on this journey.

My first thanks go to my supervisor, Associate Professor Susan Krumdieck, whose remarkable perspective on the world is both challenging and compelling. Thanks for believing in me and having the prudence to let me find my own way.

Thanks also to Dr. Rev. Keith Morrison for your all-encompassing awareness of a bewildering breadth of subjects and especially for your remarkable ability to perceive and integrate the connections between all manner of seemingly disparate concepts. Time spent with the SCDRI was always revitalising on an intellectual, emotional and a spiritual level.

Thank you to Dr. N. John Peet (I finally found out what the N stands for!) for steering me in the right direction when all I had was the vaguest notion of what I wanted to achieve. Your astute perception and sage advice are always welcome.

Huge thanks are due to Prof. Pat Bodger for your infectious curiosity and big heart. Our meeting was surely synchronicity of the greatest magnitude. Our discussions were always enlivening and exhilarating. Your infallible support always came through when it was most needed.

Thanks to all of the AEMS Lab crew. It has been a pleasure working with each and every one of you. The lunch meetings will be fondly missed. Thanks to Dr. Mark Jermy, Dr. Shannon Page and Dr. Eli Van Houten for advice on structure and last-minute editorial advice. Thanks also to other members of the Department including Ron Tinker, Eric Cox and Gerry Kirk for their help in various projects.

Special thanks to the Keith Laugesen Trust and to the Department of Mechanical Engineering for their financial assistance over the last three years, without which this work would not have been possible.

Thanks to the support of my family to get me here and lastly, thanks to my beautiful partner, Dr. India Whitehouse, for your unconditional love and support and for your amazing wisdom and patience.

Further thanks also to Prof. Adam Brandt. Your support and willingness to go ‘above and beyond’ since the first moment we met has been hugely appreciated.

ABSTRACT

The aim of this thesis is to take a broad conceptual overview of the global energy system and investigate what the aims of sustainability might entail for such a system. The work presented uses a biophysical economic approach in that the dynamics of the global economy are investigated using the tool box of the physical sciences, including the laws of thermodynamics and the methods of energy analysis.

Modern society currently uses approximately 500 exajoules (EJ = 10^{18} J) of total primary energy supply (TPES) each year. This energy consumption has been increasing at roughly 2% per year for the past two hundred years. TPES is currently dominated by three non-renewable energy sources: coal, oil and gas which, together with energy from nuclear fission of uranium, make up around 85% of the energy market. Consumption of finite resources at a continuously growing rate is not sustainable in the long-term. A trend in policy direction is to seek a transition to renewable sources of energy. This thesis seeks to explore two questions: are the technical potentials of renewable energy sources enough to supply the current and/or projected demand for energy and what would be the effect on the physical resource economy of a transition to an energy supply system run entirely on renewable energy sources?

The Global Energy Model using a Biophysical Approach (GEMBA) methodology developed here is compared and contrasted with other approaches that are used to study the global energy-economy system, including the standard neoclassical economic approach used in such models as MESSAGE and MARKAL.

A number of meta-analyses have been conducted in support of the GEMBA model. These include:

- meta-analysis of historic energy production from all energy sources;
- meta-analysis of global energy resources for all energy sources;
- meta-analysis of energy-return-on-investment (EROI) for all energy sources.

The GEMBA methodology uses a systems dynamic modelling approach utilising stocks and flows, feedback loops and time delays to capture the behaviour of the global energy-economy system. The system is decomposed into elements with simple behaviour that is known through energy analysis. The interaction of these elements is captured mathematically and run numerically via the systems dynamics software package, VenSim. Calibration of the model has been achieved using historic energy production data from 1800 to 2005.

The core of the GEMBA methodology constitutes the description of a dynamic EROI function over the whole production cycle of an energy resource from initial development, through maturation to decline in production, in the case of non-renewable resources, or to the technical potential in the case of renewable resources.

Using the GEMBA methodology, the global energy-economy system is identified as a self-regulating system. The self-regulating behaviour acts to constrain the amount of total primary energy supply that the system can produce under a renewable-only regime. A number of analyses are conducted to test the sensitivity of the system to such changes as:

- an increase of the technical potential of renewable resources;
- technological breakthroughs which would significantly increase the EROI of renewable resources;
- a decrease in the capital intensity of renewable resources and;
- an increase in the energy intensity of the economy,

A statistical analysis reflecting the wide range of values of both the estimates of EROI and technical potentials of renewable energy sources has also been undertaken using a Monte Carlo approach.

The results from the modelling suggest that not all levels of energy demand projected by the WEA can be supplied by an energy system running solely on renewable energy. The Monte Carlo analyses suggest that reduction in total energy yield over current (2010) levels might occur with a 20-30% possibility. The middle and high growth scenarios from the WEA are greater than 95% of all scenarios modelled, hence seem unlikely to be sustained by an energy system running solely on renewable energy. This finding has implications for the future direction of both engineering and technology research as well as for energy policy. These implications are discussed.

GLOSSARY

Capital Intensity: a measure of the amount of human-made-capital that must be installed in order to convert energy resources into useful forms; represented in the GEMBA model by the parameter CAPITAL FACTOR.

Dynamic system: a group of interacting, inter-related or inter-dependent elements forming a complex whole.

Economy: the sum total of all human-made-capital which is decomposed into two sectors: the energy sector and the main economy.

Energy-Economy System: the economy conceived of as two sectors, the energy sector and the main economy, in dynamic interaction.

Energy Resources: any natural capital of use for the production of energy, e.g. crude oil, coal, solar radiation.

Energy Sector: the sum total of all human-made-capital directed to the purpose of extracting energy resources and converting them into useful forms.

Ergodic: any system in which the time averaged behaviour of the system is statistically similar to the ensemble average behaviour of an ensemble of such systems each with slightly varied initial conditions, i.e. the path of the system through time is independent of initial conditions.

Feedback: when causal pathways between system elements form loop structures such that the behaviour of system elements is dependent on their own past behaviour, the arrangement is known as *feedback*

Human-made-capital: any goods produced within the economy (also called *manufactured capital*) in contrast with natural capital; represented in the GEMBA model by the parameter INDUSTRIAL OUTPUT.

Natural capital: any material or service, usually of direct benefit to humans, naturally occurring within the environment; also called *natural resources*.

Production cycle: the period of production of an energy resource lasting from initial development through to economic exhaustion in the case of non-renewable resources, or to development of the full technical potential in the case of renewable resources.

Self-regulating: system behaviour in which internal conditions and structures are maintained despite variation in external conditions. Such behaviour relies on the property of *feedback* amongst system elements

System: a grouping of elements that operate together for a common purpose

System dynamics: an approach to understanding the behaviour of complex systems over time usually through numerical calculation, dealing with stocks and flows, feedback loops and time-delays.

Technical potential: the total resource recoverable by a specified renewable energy technology.

Ultimately recoverable resources: that part of the resource base, including discovered, undiscovered, produced and unproduced amounts, that is producible under a specified set of costs and technologies.

CHAPTER 1. INTRODUCTION

> "By discovering ways to produce energy and to apply power, man has transformed himself from a puny being at the mercy of his environment into a creature with more power than he knows how to use well, whose environment now depends upon his grace, and whose longevity as a species depends upon his own wisdom." (E. F. Cook, 1976, p. 6)

The aim of this thesis is to take a broad overview of the global energy-economy system and investigate what sustainability for such a system might entail. Most 'long-term' perspectives are of the order of decades; some, such as the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) take a look out to 2100. The problems of prediction on such large timescales are obvious, however the issue with setting a specific endpoint for a projection is highlighted by the seemingly simple question, 'what then?'

If the predictions are motivated by issues of sustainability, then a more sensible approach is to run the model until the system has settled into a pattern of 'stability' that will not be drastically affected by such issues as resource depletion or degradation. Such an approach underpins the efforts in this thesis. The time horizon has been chosen such that it encompasses the entire production cycle of all non-renewable energy sources. From this perspective, the important question then becomes, "what level of energy consumption can renewable energy sources provide indefinitely?"

To answer this question has required the development of a Global Energy Model which uses a Biophysical Approach (GEMBA). The model is underpinned by the theories of energy analysis, which is based on the laws of thermodynamics. Two important concepts have been borrowed from this field – *net energy* and *energy-return-on-investment* (EROI). These represent means by which to characterise the *availability* and *accessibility* of all energy resources. The author has developed a dynamic function by which these concepts may be defined over the entire production cycle of an energy resource. This function incorporates both advances due to technological improvements and declining returns due to resource depletion.

The author has also identified another important characteristic of all energy sources; the *capital intensity*. This parameter defines the proportion of inputs to the energy production process that are embodied as physical capital, as opposed to being in the form of process energy. This is important since the creation of physical capital requires that energy must flow through the whole economy, including all of the processes that are ancillary to the capital production process but are necessary for the production of capital, such as growing food to feed the workers. In general production of energy from renewable sources is more capital intensive than energy from non-renewable sources, hence a greater amount of energy is required (including all indirect uses of energy within the rest of the economy) to provide renewable energy.

1.1. Motivation

> "Human beings and the natural world are on a collision course. Human activities inflict harsh and often irreversible damage on the environment and on critical resources. If not checked, many of our current practices put at serious risk the future that we wish for human society and the plant and animal kingdoms, and may so alter the living world that it will be unable to sustain life in the manner that we know. Fundamental changes are urgent if we are to avoid the collision our present course will bring about." (UCS, 1992)

This thesis is motivated by the concept of constraint. Energy resources are constrained in two important manners. Stock resources (such as coal or uranium) are limited in amount – once they're gone; they're gone. Flow resources (such as wind or hydro) are limited, not in total amount, but in the amount available at any one moment. All energy resources are in some sense finite. We might call this an *ontological* limit, often called *Malthusian*, after the economist Thomas Malthus (Malthus & Appleman, 1976).[1] Energy resources are also limited in another, perhaps more important manner; they are limited by our ability to obtain them. We might call this an *epistemological* limit, often called *Ricardian*, after economist David Ricardo (Ricardo, 1923) who first developed the principle of *diminishing returns*.[2] This thesis attempts to combine these two constraints by considering the *availability* of energy resources,

[1] Ontology is the study of *what there is*; that is the nature of existence and what things may or may not exist.
[2] Epistemology is the study of *what we know*. As such we infer the existence of ontological limits from our epistemological knowledge, i.e. by increasingly diminishing returns in our attempts to obtain resources.

how much there actually is of a particular resource, and the *accessibility* of energy resources, how easily these resources may be obtained. Availability of an energy resource is obviously measured by the magnitude of the stocks or flows of that resource. Accessibility is represented by financial cost in economic models. Energy analysts use the concept of *energy-return-on-investment* (EROI) to characterise the accessibility of a resource.

It is not only the supply of energy resources that is faced with limits. The consumption of many energy sources causes environmental damage. The most commonly discussed problem is the emission of carbon dioxide and other greenhouse gases (GHG) associated with the combustion of fossil fuels. Since we are emitting these gases in quantities greater than the assimilative capacity of the biosphere to extract them, they accumulate in the atmosphere. This accumulation may well have dramatic and long-lasting consequences for the global climate.

Why are these issues important? These issues gain their importance primarily due to the importance of energy. Energy has been famously referred to as, “the go of things” (Clerk-Maxwell, 1950) and is a measure of our ability to do work. Within modern society most of the ‘work’ is done, not by humans, but by machines directing flows of energy ultimately derived from natural resources.

A number of authors, particularly in the field of Ecological Economics, have studied the relationship between energy consumption and economic activity (Cleveland, Costanza, Hall, & Kaufmann, 1984; Cleveland, Kaufmann, & Stern, 2000; Cleveland & Ruth, 1997; J. D. Hamilton, 1983). Positive correlations between macroeconomic measures, such as GDP, and energy consumption are often discovered (Cleveland, et al., 1984) as well as microeconomic indicators, such as productivity (Charles A.S. Hall, Cleveland, & Kaufman, 1986). Perhaps more important than sustaining economic measures is sustaining current levels of human welfare. Present high yields of food production require large inputs of fossil fuel-based energy in the form of fertilisers derived from natural gas (Gever, Kaufmann, Skole, & Vorosmarty, 1991).

1.1.1. Building up a picture of the global energy system

An ‘energy system’ refers to the “combined processes of acquiring and using energy in a given society or economy” (Jaccard, 2005, p. 6). Figure 1-1 depicts a very simplified schematic of the global energy-economy system. Primary energy resources, shown on the left, are taken from nature by the energy transformation sector and processed into secondary energy ‘carriers’, such as solid and liquid fuels, or electricity. These energy carriers are then used by the rest of the economy to meet demands for energy services, space-heating, transport, etc. A wide variety of technologies are required at each step within the ‘chain’ from energy resource through to energy carrier and finally energy service. Some examples are extractive devices, such as oil rigs or wind turbines; processing systems such as refineries or electric generators and finally; energy-consuming devices such as cars or laptop computers. Energy-consuming devices, despite forming part of the energy transformation chain, are seldom included as part of the energy transformation sector, excepting those used directly within the sector to perform tasks directed towards the aim of delivering energy to the rest of the economy, such as the control system of a power plant.

Coal was the first fossil fuel to be used in large amounts. The resource is often divided into grades: *anthracite*, *bituminous*, *sub-bituminous* and *lignite*, in decreasing order of energy content, often expressed as MJ/kg. Oil and gas are often divided into conventional and unconventional resources. In the case of oil, this is generally decided by viscosity of the resource, but is also decided by the location, such as deep water or polar oil. Unconventional sources also include substances from which crude oil, or a variant, may be produced, such as *tar sands* (natural bitumen), *ultra-heavy oil* or *oil shale*. Enhanced recovery methods, wherein gas or liquids are injected into reservoirs to increase recovery rates, may also be considered as unconventional sources (Jaccard, 2005). Conventional gas is often found associated with oil, but may be found in *non-associated* reserves. Unconventional sources of gas include *coal-bed methane* wherein the gas is associated with coal seams usually extracted by fracturing the coal; *tight formation gas* (also often called *tight gas*) trapped in low permeability formations that also require fracturing to enable extraction; *geopressurised gas* (also called *ultra-deep gas*) wherein gas is dissolved in aquifers and*; gas hydrates* (also called *methane hydrates*) wherein gas is frozen within the crystal structure of ice normally located in polar regions or the ocean floor (Jaccard, 2005).

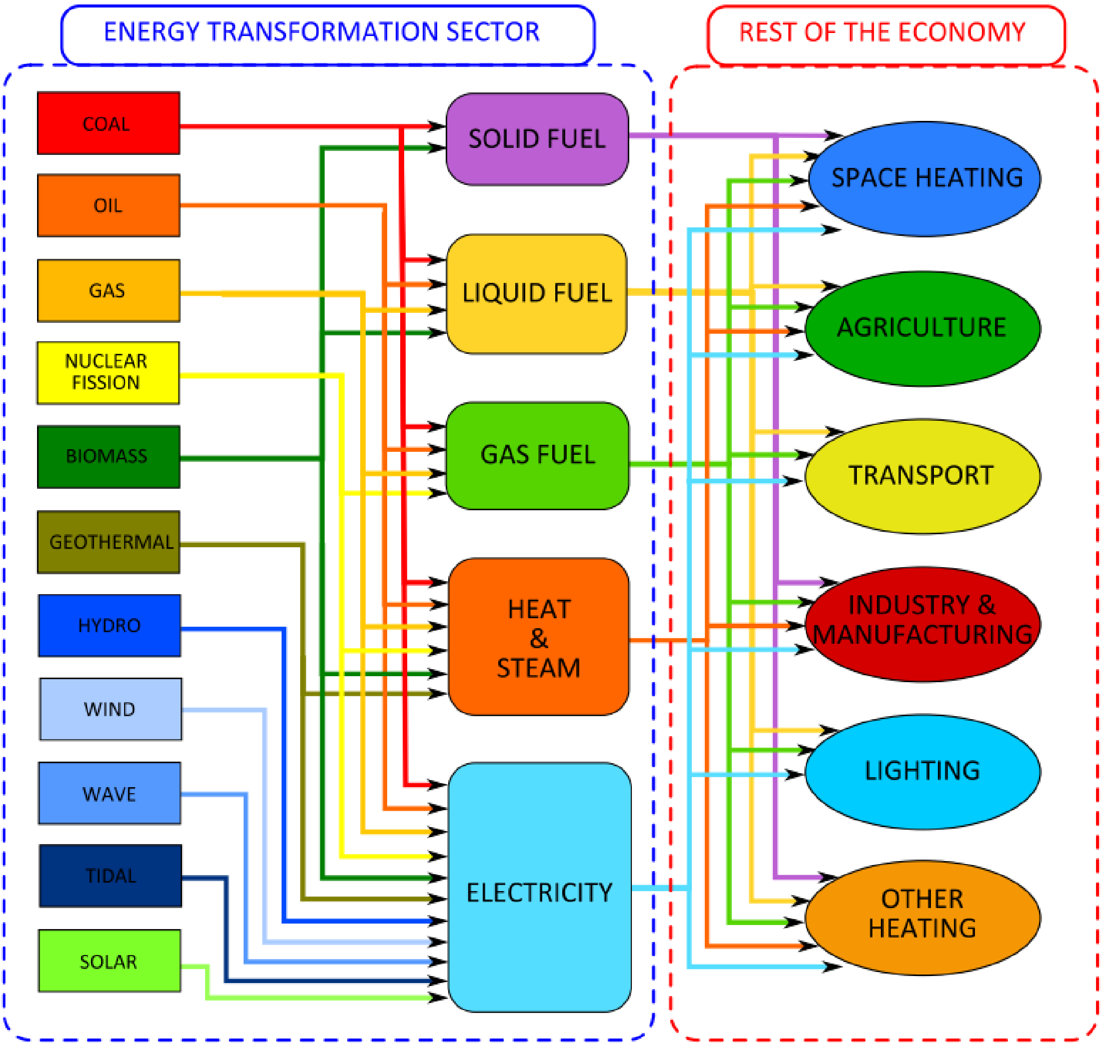


Figure 1-1. A model of the energy-economy system from energy resource through to end use

The use of fossil fuels (coal, oil and gas) has increased exponentially since the Industrial Revolution, such that in 2006, these three energy resources accounted for 398 of the 491 EJ (over 80%) total primary energy supply (TPES) of the global economy (IEA, 2008c). Energy from the fission of uranium has expanded since the fifties to produce 30 EJ of TPES in 2006.

The use of *biomass* has increased from the traditional form of use, burning directly for heat and cooking, to include combustion of solid biomass to generate electricity or processing into liquid and gas fuels. Biomass is the most commonly used form of renewable energy, producing 50 EJ of TPES in 2006. Electricity generated from the energy of falling water, *hydroelectricity*, has been in use since the late nineteenth century and now accounts for around 11 EJ of TPES. Energy from other renewable sources (mainly *geothermal*, *solar* and *wind*) accounted for only 3 EJ in 2006.

Novel means of extracting energy from renewable flows include *wave energy extraction*, a number of competing designs for which are currently being tested; *tidal*, either in the form of barrages, such as at La Rance, France, or by devices similar to submarine wind turbines and; *ocean thermal energy conversion* (OTEC) which exploits the difference in temperature between surface and (typically 1km) deep ocean water to drive a low temperature heat engine.

Figure 1-2 and Figure 1-3 depict annual production of various energy sources on a linear and logarithmic plot, respectively (estimates of historic production of each of the energy sources are plotted in Appendix A). Total primary energy supply has increased at roughly 2% per year for the past two hundred years (Etemad & Luciani, 1991; Grübler, 1998; Grübler, Jefferson, & Nakicenovic, 1996). How long can this trend continue before resource constraints disrupt energy supplies? The present, near total reliance on fossil fuels seems obviously unsustainable, however some authors argue that unconventional sources of oil, such as oil sands, and gas can provide plentiful supplies and be burned to avoid greenhouse gas emissions such that their use may be considered ‘sustainable’ (Jaccard, 2005).

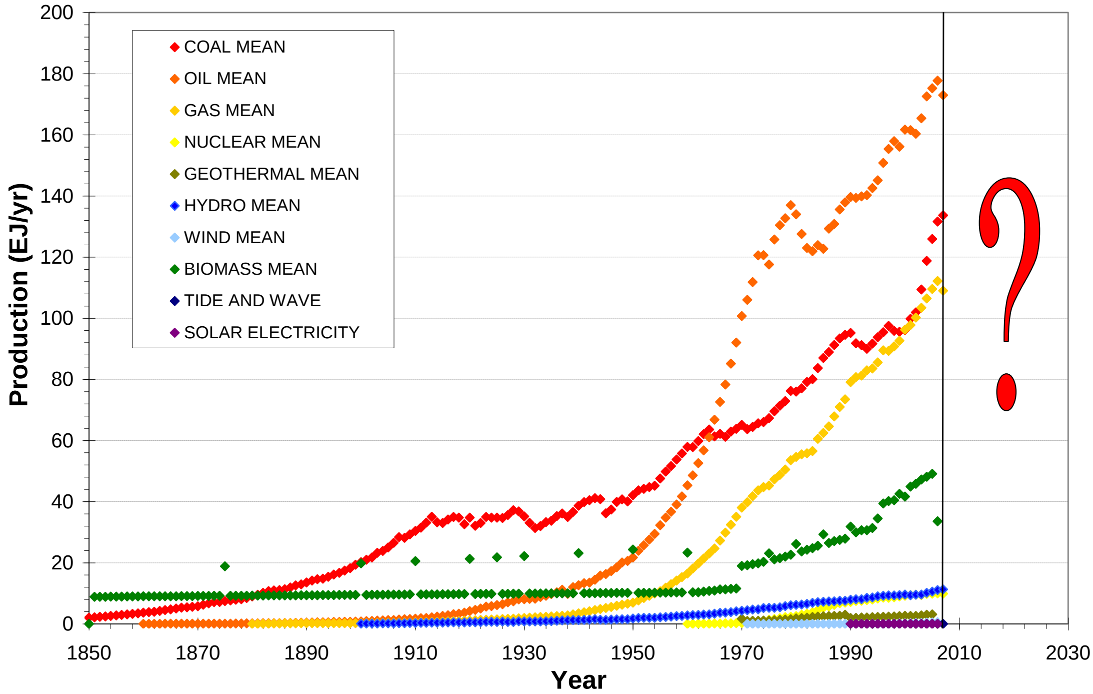


Figure 1-2. Annual production from all energy sources.
Energy production is currently highly dependent on fossil fuels. How will the energy system evolve as stocks of finite energy resources are further depleted?

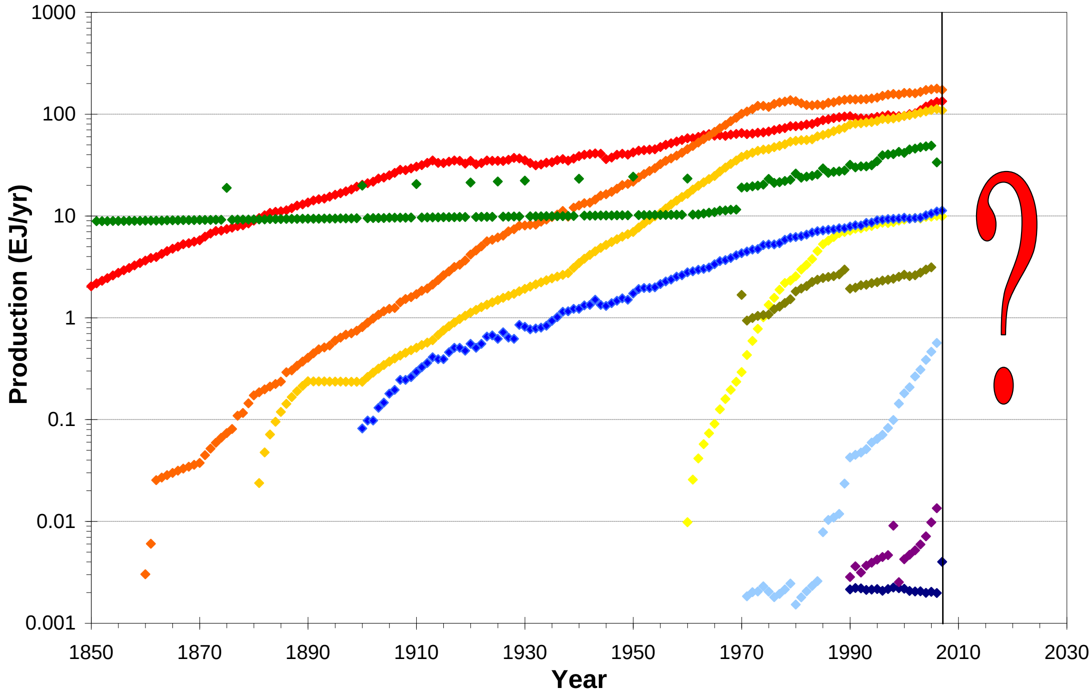


Figure 1-3. Annual production from all energy on a logarithmic plot.
Each horizontal line represents a ten-fold margin. Note the initial rapid increase in production of many energy sources (especially oil and gas) upon entering the market before proceeding at a slower rate.

1.1.2. Sustainable development

Sustainable development is a term that has gained much currency in recent years. Despite the proliferation in the literature, there is little consensus over the meaning of the term 'sustainable development', nor means by which it may be achieved (Charles A. S. Hall, 2004; Marshall & Toffel, 2005).

The idea of combining economic and social development with environmentally acceptable standards of resource consumption and pollution has been gaining steam since the environmental movement of the fifties and sixties (SDC, 2009). The notion of sustainable development (although not referred to explicitly) gained international recognition through the UN Conference on Human Environment held in Stockholm, Sweden in 1972 (SDC, 2009). A number of other key publications during the same year, including the Club of Rome's 'Limits to Growth' (D. H. Meadows, Meadows, Randers, & Behrens III) and Ecology Magazine's 'Blueprint for Survival' (Goldsmith), brought the issue further into public awareness.

The term 'sustainable development' was popularised and given the rigorous definition as "development which meets the needs of the present without compromising the ability of future generations to meet their own needs" (UN, 1987) by the United Nations Report of the World Commission on Environment and Development, often referred to by its subtitle, 'Our Common Future' or as the 'Brundtland Report' for its lead author Gro Harlem Brundtland.

The United Nations Conference on Environment and Development (UNCED) –the 'Earth Summit' – held in Rio de Janeiro, Brazil, offered an opportunity for 172 nations to further discuss the issue of sustainable development, resulting in the formation of the Commission on Sustainable Development (UN, 1997). This Commission was responsible for organising the World Summit on Sustainable Development (WSSD) held in Johannesburg in 2002, which identified five essential areas for focussing action towards achieving "sustainable livelihoods for all": *water and sanitation*, *energy*, *health*, *agriculture*, and *biodiversity*, known collectively by their acronym – WEHAB (UN, 2002, p. 86).

Within New Zealand the Parliamentary Commissioner for the Environment (PCE), a state-appointed environmental ombudsman independent of Government, has focused investigations on: *resource management*, *sustainable land management*, *tangata whenua* (the indigenous peoples of New Zealand), *waste*, *energy*, *marine environment*, *biodiversity* and *biosecurity*, and *tourism* (PCE, 2002, p. 27).

Concepts of sustainable development

A number of useful ideas have arisen to help conceptualise sustainable development. Often the issue is discussed with reference to the maintenance of various stocks of resources, or ‘capital’: *natural*, *social* and *economic*. Distinction is often made between differing conceptions of sustainable development or ‘sustainability’. Within the perspective of weak sustainability, the three forms of capital are seen as related yet independent, with some common ground between them (see Figure 1-4). This model requires only that the total capital stock be maintained and assumes that parts may be substituted between the capitals. From this perspective economic capital is given priority and may compensate for degradation within the other stocks (PCE, 2002, p. 34).

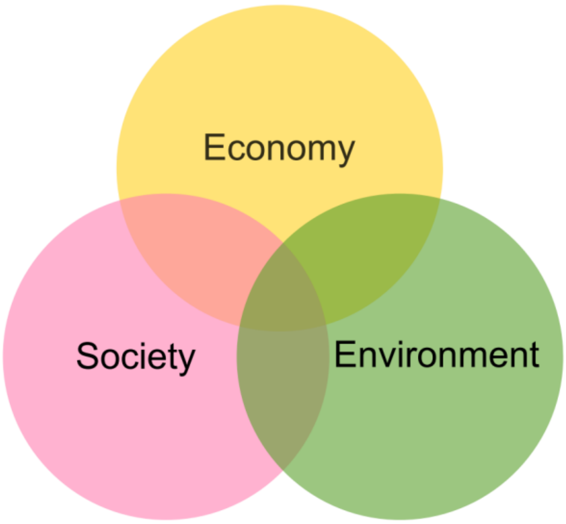


Figure 1-4. Venn diagram of weak sustainability.
Economic, social and environmental aspects are independent but connected. Economic capital is given priority and may compensate for degradation within the other stocks

In contrast, the model of strong sustainability, as represented in Figure 1-5, recognises the economy as a sub-set of society, itself constrained by natural systems. Human systems are seen as totally dependent on natural systems for their existence, and each of the parts (nature, society and the economy) must be maintained separately with only limited potential for substitution (PCE, 2002, p. 35).

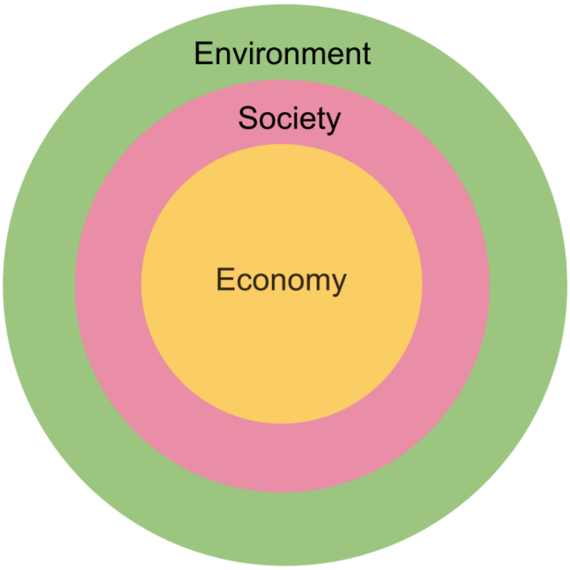


Figure 1-5. Model of strong sustainability.
The economy and society are a sub-set of natural systems. Each of the parts (nature, society and the economy) must be maintained separately with only limited potential for substitution

Definitions of sustainable development

Since the inception of the Commission on Sustainable Development at the Earth Summit, a number of national governments and individuals have developed definitions to encapsulate their perception of sustainable development.

The Organisation for Economic Co-operation and Development (OECD, 2001) has identified four criteria for environmental sustainability:

- **Regeneration:** using renewable resources efficiently and not permitting their use to exceed their long-term rates of natural regeneration.
- **Substitutability:** using non-renewable resources efficiently and limiting their use to levels that can be offset by substitution by renewable resources or other forms of capital.
- **Assimilation:** not allowing releases of hazardous or polluting substances to the environment to exceed the environment's assimilative capacity.
- **Avoiding irreversibility:** avoiding irreversible impacts of human activities on ecosystems.

The UK Government Sustainable Development Strategy (UK Govt., 2005, p. 15) defines sustainable development as the integration of four objectives :

- social progress which recognises the needs of everyone
- effective protection of the environment
- prudent use of natural resources
- maintenance of high and stable levels of economic growth and employment

The achievement of these objectives are to be undertaken within the framework of five guiding principles (UK Govt., 2005, p. 16):

- Living within environmental limits
- Ensuring a strong, healthy and just society
- Achieving a sustainable economy
- Promoting good governance
- Using sound science responsibly

Whether the goal of maintaining "high and stable levels of economic growth" is consistent with that of "living within environmental limits" is not obvious. Other authors see a direct connection between the two objectives. Costanza (1994) conceives sustainability as a long-term policy objective requiring:

- a sustainable scale of the economy relative to its ecological life-support system
- a fair distribution of resources and opportunities between present and future generations, as well as between agents in the current generation
- an efficient allocation of resources that adequately accounts for natural capital

1.2. Defining the research problem

Definitions of sustainable development imply that continued use of non-renewable energy resources is unsustainable both in terms of the finitude of such resources but also the damaging environmental consequences associated with their use. Such a conclusion suggests that the only sustainable option for the energy system is to make a transition to renewable energy sources. Such a transition raises some questions:

- Are the technical potentials of renewable energy sources enough to supply the current demand for energy or is energy descent inevitable?
- What would be the effect on the physical resource economy of a transition to an energy supply system run entirely on renewable energy sources?

Such questions underpin the philosophical drive of this thesis. In particular the question, "can renewable energy sources provide enough energy to support current energy consumption?" This question has been addressed by MacKay (2008) in his book *Sustainable Energy – without the hot air*. MacKay's analysis offers a 'snapshot' of current energy consumption and the potential of renewable energy resources to meet that consumption. His analysis, however, fails to account for two very important factors. Firstly, it is not simply gross energy but *net energy* (that is the energy provided by the energy sector *less* the energy required to obtain that energy) which is important to society. Secondly, renewable energy sources require greater physical capital investments than do fossil fuels in order to obtain an equivalent amount of energy. This is a necessary consequence of the dilute energy fluxes of environmental flow energy sources, such as solar insolation, air or water flow, compared to the high energy density form of fossil fuels.

Many authors feel that the potential of renewable energy sources is more than adequate to supply both current and future energy needs.

> "Renewable energy sources can meet many times the present world energy demand, so their potential is enormous. They can enhance diversity in energy supply markets, secure long-term sustainable energy supplies, and reduce local and global atmospheric emissions" (WEA, 2000, p. 220)

> "Renewable energies have considerable potential and could theoretically provide a nearly unlimited supply of relatively clean and mostly local energy" (WEC, 2003, p. 2)

> "Technological advances offer new opportunities and declining costs for energy from renewable sources which, in the longer term, could meet a major part of the world's demand for energy" (IPCC et al., 2001, p. 235)

> "Renewable energy sources have enormous potential and can meet many times the present world energy demand" (Asif & Muneer, 2007, p. 1396)

> "Given adequate support, renewable energy technologies can meet much of the growing [energy] demand at prices lower than those usually forecast for conventional energy" (Thomas B. Johansson & Burnham, 1993, p. 1)

> "Nuclear power and almost each form of renewable energy are capable of collectively meeting the needs of a significantly expanded human energy system on a continuous basis." (Jaccard, 2005, p. 162)

> "Special energy crops can provide ample biofuel feedstocks" (Lovins, 2004, p. 107)

> "An entirely renewable and thus sustainable electricity supply is possible with today's technology" (Czisch, 2004)

> "Solar energy can replace fossil and nuclear fuels over the next 50 years, thus creating a truly sustainable energy supply system." (Blakers, 2004, p. 109)

> "Major types of renewable energy sources include solar, wind, hydro and biomass, all of which have huge potential to meet future energy challenges" (Rizwan, Jamil, & Kothari, p. 1)

> "The results of the FFES [Fossil Free Energy Scenario]… confirm that it is possible to phase out both fossil fuels and nuclear power and thus avoid climate disaster" (Lazarus et al., 1993, foreword by Greenpeace)

> "Fortunately most countries rich in coal are plentifully endowed with solar and wind renewable nonemitting energy reserves that can gradually replace coal economically" (Abt, 2002, p. 108)

A number of other authors including Nicholas Georgescu-Roegen (1975), David Holmgren (2002), Ted Trainer (2007) and Lloyd and Forest (2010) however, believe that renewable energy sources are not adequate to supply current energy consumption levels achieved by the combustion of fossil fuels, let alone potentially increased levels in the future. The aim of this thesis is to examine this issue, expressed in this statement from Kozo Mayumi (1999),

> "It remains unclear whether or not solar technology can completely replace fossil and fissile fuels. It is an open question as to whether or not solar energy technology will remain a 'parasite' to fossil and fissile fuels." (p. 190)

The basic structure of the argument proposed in this thesis, runs as follows:

1. Assumption – unsustainable practices cannot be continued indefinitely.
2. Assumption – exosomatic energy sources are necessary for the continued function of present-day society (Tainter, 1988).

Therefore

3. Conclusion – we require sustainable sources of energy
4. Assumption – finite stocks of resources (i.e. fossil and fissile fuels) can not be used indefinitely[3]

Therefore

[3] Whilst it may be possible to prove that theoretically a finite stock may last forever with an exponentially declining consumption, this is not much use for practical purposes. The issue of fusion (for which the resource is could be considered infinite) is discussed in Chapter 7)

5. Conclusion – we must (someday) obtain all of our energy needs from renewable energy sources

Given this conclusion, it would seem of vital importance to explore and attempt to answer the question “can renewable energy sources supply current levels of energy consumption?” If they cannot, it would seem that most development and energy policy is heading in the direction of increasing unsustainability. Indeed it would seem that this possibility has not even entered the minds of many policy makers. We are more normally presented with energy demand as an ever-increasing uphill march on 20-30 years into the future simply begging the question, ‘What then?’ Such projections are often justified by the combination of population growth and increasing material living standards (Jaccard, 2005). However, few countries worldwide are contemplating or extolling, let alone planning, for decreasing energy consumption in the future, even those with stable or decreasing populations. Energy policy based on the recognition that renewable energy sources might not be able to cope with current consumption levels might be somewhat different than current policies. Presumably, since any ‘uphill’ increase might mean further to ‘fall’ on the other side of the peak, the emphasis would be on conservation of precious energy resources.

1.3. Thesis organisation

The structure of the thesis is organised around the argument laid out in Section 1.2. This serves as the backbone for the work presented. Assumption 1, that “unsustainable practices ultimately entail social collapse” should be self-evident from the definition of the term ‘sustainable’. The basic premise is that, over a long enough timescale, what is unsustainable will perish.

Assumption 2, that “present day society depends on energy” may take a little more explanation. That energy is used by modern society is evident by the large and increasing flows produced each year, as depicted in Figure 1-2 and Figure 1-3. That society is dependent on such energy flows stems from the fact that most economic ‘work’ is achieved by utilising energy contained, primarily, within fossil fuels. Within industrialised societies, it is rare that humans are employed merely for their ability to ‘do work’ in the thermodynamic sense. More often the role of an employee is to oversee the output of a machine or to make decisions (Malcolm Slesser, King, & Crane, 1997).

The conclusion, 3, from assumptions 1 and 2 is that “we require sustainable sources of energy”. This conclusion should be self-evident. If in order to avoid collapse, society needs to undertake sustainable practices and that present day society depends on such energy flows then, in order to sustain society the sources of energy must themselves be sustainable.

This conclusion highlights the importance of energy as the basis for all activity within society. It could further be argued that the converse is also true, that a society without a sustainable energy system cannot be considered 'sustainable'.

Assumption 4 is that "finite stocks of resources (i.e. fossil and fissile fuels) can not be used indefinitely." This assumption should also be self-evident. Proponents of nuclear technology argue that current resources of uranium are plentiful enough to supply our energy needs long into the future, especially when 'breeding' technologies are used. The issue of 'breeder' reactors is discussed in CHAPTER 5. The basic facts are that, of the seven breeder reactors built, only one is still operational, however two new plants are currently under construction (IAEA, 2008). Some proponents of fossil fuels similarly claim that coal resources and unconventional sources of oil and gas are large enough that they may be used for such long periods as to render their use 'indefinitely' long (Jaccard, 2005). The basis of this claim is investigated in CHAPTER 6. Estimates of potential non-renewable and renewable resources are listed in Appendix B.

Conclusion 5 is that, in order for our energy system to be sustainable, "we must obtain all of our energy from renewable sources." This conclusion stems from the conclusion that we require a sustainable energy system and that finite resources may not be used indefinitely, especially at increasing rates of consumption, as is currently the case. Some economists claim that increasing prices due to supply shortages relative to demand will inspire increasing activity in exploration and technology thus expanding reserves (Peter R. Odell, 1973). In this sense resources are not finitely limited. If measured in terms of price, scarcity of many 'non-renewable' resources seem to have decreased over the twentieth century (Barnett & Morse, 1963). Others have argued that the fall in prices belies increasing energy inputs (Cleveland, 1991) and may well falsely signal decreasing scarcity (Georgescu-Roegen, 1975; D. B. Reynolds, 1999).

Given a long enough timescale, the *availability* of all finite resources must be depleted by consumption. Similarly, non-renewable resources (both energy and other minerals) have become less *accessible* (as measured by the energy consumed in their extraction) as production of them continues (P. F. Chapman & Roberts, 1983; Cleveland, 2005; Charles A.S. Hall, et al., 1986; Mudd, 2007; Page & Creasey, 1975). Only renewable energy sources avoid both of these issues in the long run, since they are unlimited in total quantity.

The rest of this thesis involves an exploration of the question "can renewable energy sources supply current levels of energy consumption?" This involves the development of a biophysical model of the energy-economy system,

CHAPTER 2 gives an outline of the theoretical background necessary for understanding the development of the Global Energy Model using a Biophysical Approach (GEMBA) model. This includes an overview of systems theory and the contrast of two world views: the economic perspective and the biophysical systems perspective. The chapter then proceeds with a discussion of the philosophical underpinnings of modelling and some modelling techniques. Finally, the basics of energy analysis are discussed as well as some of the concepts that are needed later, such as *net energy* and *energy-return-on-investment* (EROI).

In CHAPTER 3, a number of existing energy models are discussed. These models have been divided into three categories:

1. Deterministic models which use growth curves to forecast future energy production.
2. Economic models which forecast the investment necessary in the energy system to respond to changing energy demand.
3. Biophysical models which characterise economic activity in terms of availability and supply of energy resources.

The adequacy of these models is discussed. The conclusion is that there is a need for a model incorporating an EROI function which changes over the lifetime of production of an energy source. This function is presented and developed in CHAPTER 4.

CHAPTER 5 gives a description of the GEMBA model structure, and the key variables and relationships between them. This chapter also describes the assumptions underlying the model's construction and outlines the data requirements of the model.

CHAPTER 6 outlines the data necessary to give context for the GEMBA model parameters $\text{URR}_{\text{NON-RENEWABLE}}$, $\text{TP}_{\text{RENEWABLE}}$, PEAK EROI, and CAPITAL FACTOR. This includes an assessment of estimates of energy resource availability (stocks of ultimately recoverable resources (URR) of non-renewable energy and technical potentials (TP) of renewable energy)[4]; meta-analysis of EROI values for all of the energy sources used within the model[5] and; an assessment of estimates of physical capital inputs into energy production processes.

[4] Estimates of potential resources are listed in Appendix B

[5] Estimates of EROI of energy resources are listed in Appendix C

In CHAPTER 7, the model results are analysed. Calibration to historical data is described. The model is run for future time periods and the sensitivity of the model output to varying inputs is assessed. Analysis is then made of the sensitivity of the model outputs to changes in those variables which reflect the way in which society uses energy, such as increasing energy intensity. The wide range in possible values for the GEMBA input parameters defines a 'possibility space' for the output variables. In CHAPTER 8, more of this possibility space is explored, using three methods: a case-study of solar energy; mapping the boundaries of the possibility space and; statistically mapping the landscape of the possibility space using a Monte Carlo analysis. The results of the preceding chapters are discussed in CHAPTER 9. The dynamics of the GEMBA model are also explored further.

CHAPTER 10 gives a revision of the main assumptions of the GEMBA methodology and explores their effects on the results from the model. Implications of the model results for engineering and technology research and for energy policy are then considered. The chapter ends with some conclusions for the research as well as by indicating fruitful avenues of further investigation.

CHAPTER 2. PRELIMINARY THEORETICAL CONSIDERATIONS

This chapter serves to introduce the reader to several fundamental concepts that underpin much of the work contained in later chapters. The integration of three main paradigms: systems theory, dynamic modelling and energy analysis forms the conceptual basis for the biophysical model of the global energy model presented within the methodology section.

The first section gives an overview of the basic concepts of systems theory, several types of systems and two fundamental ways of viewing the world: the economic and the biophysical systems world views.

The second section gives a brief overview of energy analysis including some of the tools, methods and concepts, particularly those of *net energy yield* and *EROI*.

The third section deals with modelling; describing some basic concepts, different motivating purposes for producing models and the modelling process. Different approaches to energy modelling (i.e. models that attempt to predict future states of the global energy system) are investigated with a particular emphasis on econometric and biophysical systems energy models.

2.1. Systems theory

> "Depending on your philosophical point of view, systems may be either the actual building blocks of nature or, instead, an effort by man (like taxonomy) to impose order upon the seeming chaos of nature." (Charles A. S. Hall & Day, 1990, p. 6)

Systems theory grew out of the recognition of analogies across work within several different disciplines including developmental biology (H. Maturana & Varela, 1972), ecology (Odum, 1983), cybernetics (Wiener, 1948), systems engineering (A. D. Hall, 1962), organisational theory and system dynamics (Forrester, 1972) and psychology, especially family systems theory (Bateson, 1972). The systems approach is an attempt to collect the similarities across these fields into a general scientific schema and, as such, offer a means by which to conceptualise the behaviour of systems as an aid to workers within those disciplines and a means for communication across disciplines (Bertalanffy, 1971).

2.1.1. What are systems?

Systems have been characterised in a number of ways by different authors: as "a grouping of parts that operate together for a common purpose" (Forrester, 1972, pp. 1-1), as "any phenomenon, either structural or functional, having at least two separable components and some interaction between these components" (Charles A. S. Hall & Day, 1990, p. 6) or as "a whole that cannot be divided into independent parts" (J. Peet, 1992, p. 73). The common theme between all of these definitions is the idea of a system being composed of separable components but also further that "each part has properties it loses when separated from the system. Every system has some essential properties that its parts do not have" (J. Peet, 1992, p. 73).

The systems approach focuses on the interactions or patterns of behaviour between elements rather than on the objects themselves (J. Peet, 1992). This shift in focus has been accompanied by a realisation that many relational aspects of a system are not able to be represented in purely quantitative terms and so a corresponding shift toward qualitative descriptions is also found (H. R. Maturana, 1975).

2.1.2. Types of systems

Systems are often categorised as different types, corresponding to differences in the properties, purpose and behaviour of the systems.

Hard and soft systems

One of the primary distinctions made between systems is between *hard* and *soft* systems. In general, *hard systems* include the sorts of systems that are manufactured, such as computers, cars or buildings. These systems are often built with a particular purpose in mind and are composed of identifiable elements. The interactions between individual elements in such systems are usually easily determined, and are often represented via mathematical relationships (Fishwick, 2007; B. M. Hannon & Ruth, 2000). The purpose of considering *hard systems* is often to discover appropriate methods for controlling their behaviour (Khisty & Mohammadi, 2001)

In contrast, *soft systems* are indeterminate in both purpose and behaviour, often composed of elements that may be characterised in many different ways, the classic example being a social system (J. Peet, 1992). Since the *hard system* approach is often inappropriate for such systems, *soft systems thinking* offers a way of thinking about social systems (Checkland & Scholes, 1990).

The existence of people within a system does not necessarily preclude being able to define quantitative relationships between system elements, in fact much of the early application of system dynamics was within organisational structures such as businesses (Forrester, 1971, 1972).

Isolated, closed and open systems

An isolated system is one that is disconnected from its environment in such a way as to prevent the exchange of either energy or material. Since, in reality, all systems must be coupled at least somewhat with their environment, this concept is an idealisation, but is representative of systems with a degree of isolation from their surroundings as depicted diagrammatically in Figure 2-1. Energy and materials may be exchanged between the elements of the system but may not cross the system boundary.

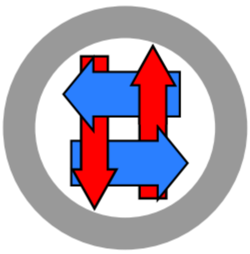


Figure 2-1. Diagrammatic representation of an isolated system.
An isolated system exchanges neither energy (red arrows) nor materials (blue arrows) with its environment. Since all real systems are coupled with their environment, a truly isolated system is an idealised construction, an example being a perfectly insulated container

A closed system is one that can exchange energy, but not materials, with its surrounding environment, as depicted in Figure 2-2. The Earth is often considered a closed system since the exchange of matter (in the form of meteorites and losses of atmospheric gases) is negligible compared to the large flux of solar radiation (insolation). According to the first law of thermodynamics, any difference in incoming and outgoing energy across the system boundary must be equal to the change in internal energy of the system. In the case of the Earth, the magnitude of insolation is equal to the amount of heat energy leaving the Earth. The in-coming energy is of a lower entropic value than the out-going infra-red radiation and this degradation in free energy powers practically all of the biological systems on Earth.

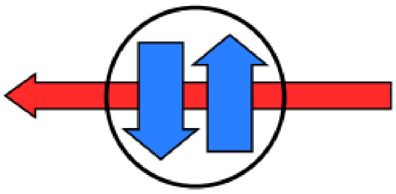


Figure 2-2 Diagrammatic representation of a closed system.
A closed system exchanges energy (red) but not matter (blue) with its environment. The Earth is often considered a closed system since the exchange of material with outer space is negligible compared to the large flux of solar energy (insolation)

An open system may exchange both energy and materials with its environment. The system boundary of such open systems may be physically well-defined, such as the ocean; however it may also be a conceptual boundary, such as the Tasman Sea. The human energy-economy system is an open system since it exchanges both material and energy with the surrounding environment. The biosphere is an open system, since it is open to energy from insolation and has material in- and outflows due to subduction at tectonic plate boundaries and volcanism. The human energy-economy system is likewise an open system since it exchanges both matter and energy with its environment.

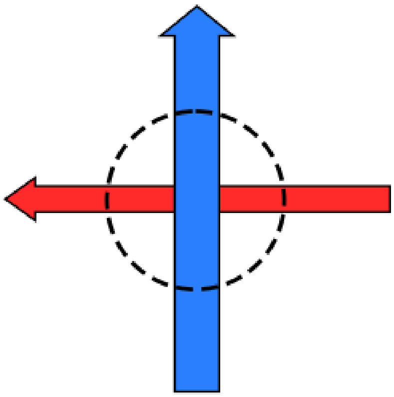


Figure 2-3 Diagrammatic representation of an open system.
An open system exchanges both energy and matter with its environment. The ocean would be an example of an open system, since it has a well defined boundary with large flows of materials across that boundary

Self-regulating systems

Living systems make use of their ability to exchange matter and energy in order to maintain their internal structures by ‘exporting’ entropy to (or importing ‘neg-entropy’ from) their surroundings (Schrödinger, 1944). Such maintenance of internal conditions and structures is known as *self-regulation*. Non-living systems may also be self-regulating, as in the case of a temperature-controlled oven. Such self-regulation relies on the property of *feedback* amongst system elements.

Self-organising systems

Self-organising behaviour involves the spontaneous increase in complexity of the internal structure of a system. Such behaviour is often observed in systems far from equilibrium, such as the formation of convection cells in heated fluids. The *self-organising* behaviour is an *emergent property* of the system, i.e. the property cannot be explained in terms of the properties of the elements of the system.

A system is said to be *organisationally closed* (as opposed to a closed system in the physical sense) when the interaction of system elements ensures the continuation of the system’s own pattern of organisation, as opposed to an *organisationally open* system which relies entirely on external sources for determining its own pattern of organisation (Dempster, 1998, p. 30).

Ergodic and historic systems

In an attempt to give some mechanical explanation to the observations of classical thermodynamics, Boltzmann (1974) envisioned thermodynamic systems as collections of atomic ‘billiard balls’. Due to the large number of atoms constituting the fluid meaning that the initial condition of the system could not be known with certainty, the state of the system at any time, *t*, was assumed to be the statistical average of an ensemble of identical systems with different initial conditions, i.e. the particle positions and momentum, consistent with the macroscopic initial state of the system (Szasz, 2000). Crucial to this formulation is the ergodic hypothesis, that:

> “For large systems of interacting particles in equilibrium time averages are close to the ensemble average, or equilibrium average” (Szasz, 2000, p. 423)

That is, that the behaviour of one member of the ensemble, observed over a long enough period of time, will be statistically similar to the behaviour of all members at a single point in time. Such systems are said to display *ergodicity*. The converse assumption of non-ergodicity, is that the evolution of a system is dependent on initial conditions, i.e. that "history matters" (David, 2007). Such a system is said to display path dependence, or *historicity* (David, 2007).

2.1.3. Properties and characteristics of systems

Systems can display a variety of characteristics that may or may not be properties of the individual system elements.

Emergence and hierarchy of systems

Due to the non-linear, network nature of complex systems, new, 'emergent', properties can be expected to arise at each level of conceptualisation. These are properties of the system that are irreducible in terms of properties of the system's components expressible as "the nature of the whole is always different from the mere sum of its parts"(Capra, 1997, p. 29). Such system behaviour can cause the creation of *emergent structures*, examples being ripple patterns in sand dunes or convection cells in heated materials. The emergence of life from large molecular structures is perhaps the most obvious example of an *emergent property*.

Due to the increase in complexity exhibited by self-organising systems, systems may be categorised into levels of complexity, each with corresponding characteristics (see Table 2-1).

Table 2-1. Boulding's hierarchy of systems.
Each level in the hierarchy displays a degree of complexity greater than the previous level, with *emergent* properties and structures characteristic of each level.

Level	Description	Characteristic	Example
1	Structures	Static, spatial frameworks	Atom, crystal, bridge
2	Clockworks	Predetermined motion	Solar System, clocks, machines
3	Control	Closed-loop feedback control mechanism	Heater with thermostat
4	Open systems	Structurally self-maintaining	Cells
5	Genetic systems	Society of cells	Plants
6	Animals	Nervous system, self-awareness	Birds and Beasts
7	Humans	Self-consciousness, knowledge, language	Human beings
8	Socio-cultural systems	Roles, values, communication	Family, community, society
9	Transcendental systems	Beyond our knowledge	Religion

Communication and system control

Communication between system elements may be such as to allow some measure of control of the system behaviour. Such a system may be represented as a process that involves converting a certain type of input, e.g. electrical energy, into a certain type of output, e.g. radiant heat energy (see Figure 2-4). An example of such a process might be an electric heater consisting only of a resistive element in a circuit.

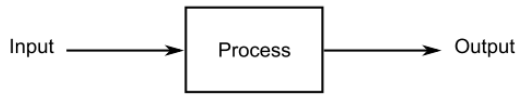


Figure 2-4 A process to be controlled.
The process consists of converting inputs into outputs, for example a heater turning electricity into heat.

A controller may be added to the system that changes the input to the process according to some desired output, such an example might be the addition of a time-setting to our electric heater. Such a system configuration is called an open-loop control system (see Figure 2-5).

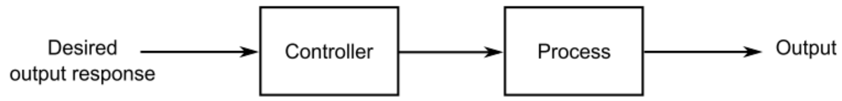


Figure 2-5 An open-loop control system.
A controller may be added to the system to control inputs to the process according to a desired output. An example of such a system is the time-setting on a toaster.

In a closed-loop control system, some means of measurement is introduced such that the output of the process may be compared with the desired output continuously during operation (see Figure 2-6). An example of such a system is a heating system with a thermostat wherein the heater (process) is controlled by the comparison between the desired result (a certain temperature) and the result of the output of the heater.

The loop structure, such that the behaviour of system elements is dependent on their own past behaviour, is known as *feedback* (Forrester, 1972).

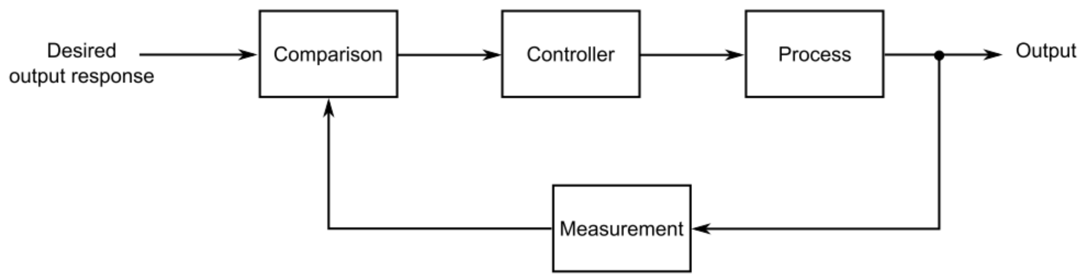


Figure 2-6 A closed-loop feedback control system.
A comparison is made between the desired and actual output of the process and the controller adjusts the process inputs accordingly. An example of such a system is a heater with a thermostat which can be set to a desired temperature.

Feedback and nonlinearity

Many other systems may be represented by using feedback loops. An example is that of the level of a population, as represented as a stock and flow diagram in Figure 2-7. The population is increased by the inflow of births and decreased by the outflow of deaths. The rate of each flow will be dependent upon the size of the population. If the birth rate (per level of population) is greater than the death rate, the population will grow exponentially. If the death rate is greater than the birth rate, the population will decrease exponentially.

The existence of feedback loops within self-regulating systems means that such systems often display non-linear behaviour, such as exponential growth or decay, or even chaotic behaviour such as erratic oscillations about a stable level. Such systems may also display *resilience*, defined as the “capacity of a system to maintain certain structures and functions despite disturbance” (Gunderson & Pritchard, 2002, p. 59), in the face of large changes in external conditions .

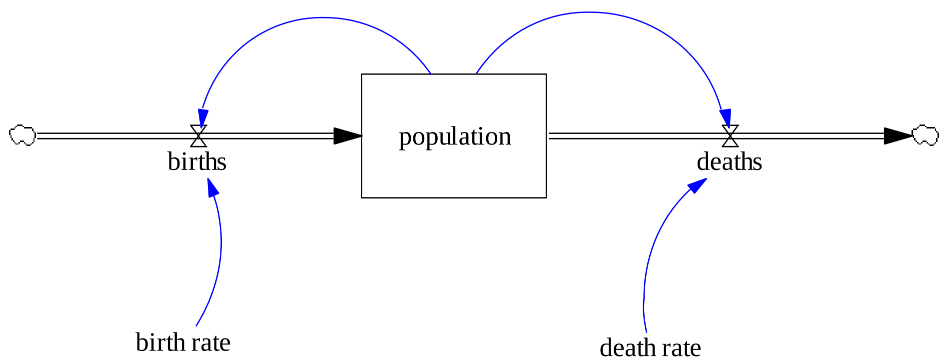


Figure 2-7 Stock and flow diagram of population.
The level of the population is increased by births and decreased by deaths. The population may either be stable, growing exponentially or decreasing exponentially

2.1.4. Human and natural systems

Both human and natural systems may be classified as complex, non-ergodic, self-organising systems, in states far from thermodynamic equilibrium. The interaction between such systems is difficult to quantify due to the possibility of spontaneous re-organisation of elements within the system in response to external stimuli (self-organisation), however general patterns of behaviour can be described between system indicators, such as ecosystem carrying capacity and human population or the size of the physical economy.

Carrying capacity is “the maximum population the environment can support” (Charles A. S. Hall & Day, 1990, p. 77) and is a function of food, water and other critical resources as well as the lifestyle of the population.

Based on the findings from the World3 model, Meadows et al. (1992) suggest four possible outcomes for such system dynamics as depicted in Figure 2-8. In the case of *continuous growth*, the size of the population enables an increase in the carry capacity which further enables population to increase. Such a coupling between population and carrying capacity is observed in advances in sanitation and health or agriculture, allowing greater numbers of people to be supported.

Many examples of populations, such as bacteria, under experimental conditions display an initial exponential growth in population followed by a decreasing growth rate up to some limit, often represented by a *sigmoid curve*. The suggestion here is that the population can have little impact on the carrying capacity and that the population can respond quickly to signals regarding impending limits.

If growing too quickly, i.e. increasing at a rate faster than its capacity to respond to appropriate signals, a population that can both positively and negatively impact on the carrying capacity, for instance through degradation of life-support systems such as soil erosion, may *overshoot* the carrying capacity which will decrease, leading to a decrease in the population. Both the population level and carrying capacity may then *oscillate* around each other ending in either a stable population at the carrying capacity, or a continual oscillation of the two. Such a case is only possible if the environment can recover quickly from degradation. Another possibility for a population that *overshoots* its carrying capacity is the *collapse* of both carrying capacity and population to a level lower than the initial level. This may be due to an inability of the environment to recover from degradation

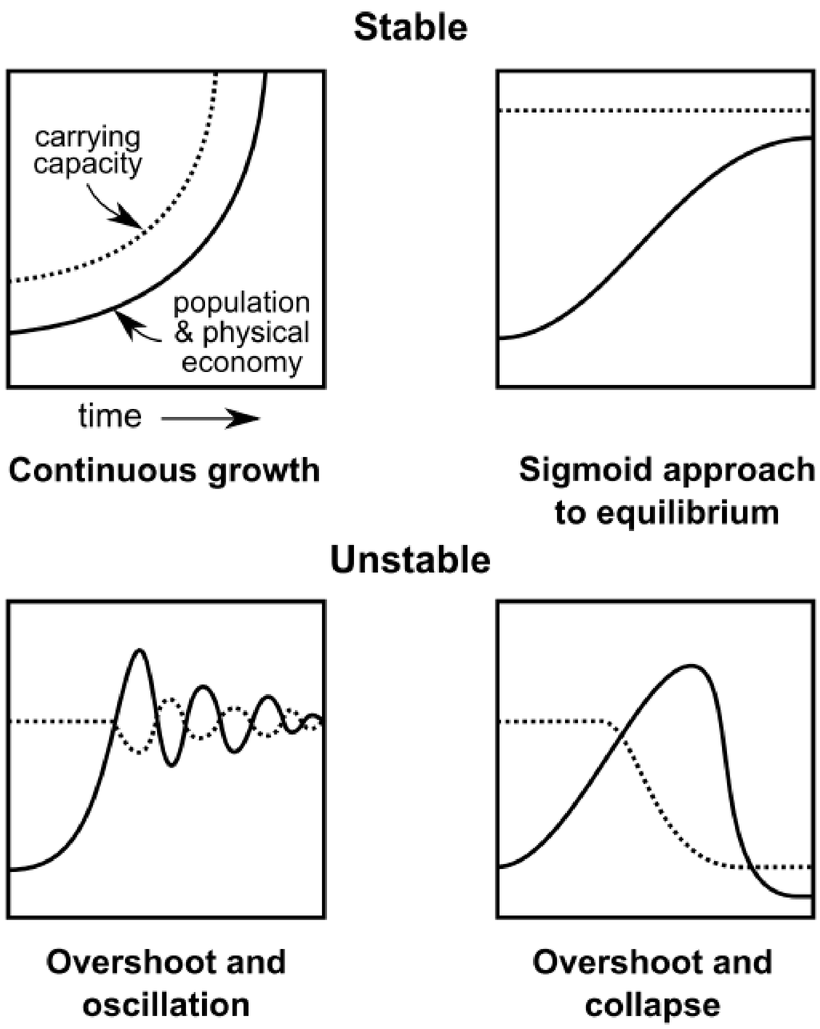


Figure 2-8. Diagrammatic representations of various relationships between population and carrying capacity from (D. H. Meadows, et al., 1992).
Continuous growth may occur if physical limits are increasing. Sigmoid growth may occur if the population can respond quickly to external limits or limits itself before such signals occur. Overshoot and oscillation may occur if response to limits is delayed and the environment is quick to recover from degradation. Overshoot and collapse may occur if response to limits is delayed and the environment is slow or cannot recover from degradation.

A number of authors have studied both ancient and contemporary cultures as social systems from the perspective of both energy and complexity (R. Adams, 1978; R. M. Adams, 2001; L. A. White, 1943). Authors in the field of ecology, particularly human ecology, have developed conceptual tools, such as the ‘adaptive cycle’, to describe the evolution of such systems (Gunderson & Holling, 2001; Holling, 2001). Some authors have focussed their research efforts on the issue of social collapse (Diamond, 2005; Tainter, 1988).

2.1.5. Two world views: economic and biophysical

The systems approach may be used to distinguish between two different views of the world: the economic and the biophysical.

The economic world view

> "From the political-economic viewpoint, the world is a place where people make all decisions of importance and human ingenuity is the main determinant of options for the future." (J. Peet, 1992, p. 47)

The economic world view (as depicted by the conventional model of the economy in Figure 2-9) sees all behaviour within the economy as determined only by processes internal to it. Consumers sell their labour to producers in return for an income with which they purchase the goods and services offered by the producers (Colander, 2004, p. 59; Daly & Farley, 2004; Gans, King, & Mankiw, 2003, p. 23).

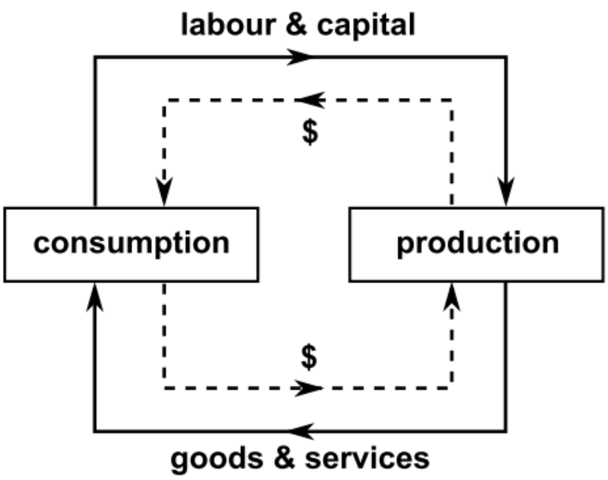


Figure 2-9. A macro-economic model of the economy as the interaction of two sections of society adapted from (Colander, 2004).
Consumers sell their labour to producers in return for an income and with that money they purchase the goods and services offered by the producers.

From this perspective, the economy may be categorised as an organisationally closed, closed-loop feedback system, which is presumably also physically open to the flow of energy and materials, although it is unclear from the model.

The important role of natural resources has not generally been acknowledged by standard economic theories (Daly, 1999; Georgescu-Roegen, 1975). A fundamental premise of economic theory is that resource scarcity will inspire technological changes to either promote more efficient use of the resource, thereby extending its lifetime, to find new deposits or to provide suitable alternatives at a comparable price (Smith, 1980).

Within economic theory, the production of natural resources is often supposed to be dependent solely on conditions within the economy. In his seminal paper *The Economics of Exhaustible Resources,* Hotelling (1931) characterised the rate of extraction as an interplay between the value of the resource if left in the ground, declining into the future due to the social discount rate, and the price the owner could receive by producing the resource in the present, determined by the demand price curve.

Empirical justification of the progress of technological change was offered by Robert Solow (1957) who analysed growth of the United States economy between 1909 and 1949. The growth in output $\boldsymbol{Y}$ was modelled by increases in capital, $\boldsymbol{K}$ and labour, $\boldsymbol{L}$ in the aggregate Cobb-Douglas production function:

$$Y(t) = [K(t)]^{\propto}[L(t)A(t)]^{1-\propto} \qquad [2\text{-}1]$$

The residual which could not be accounted for by either capital or labour, Solow attributed to 'technological change' or 'total factor productivity', $\boldsymbol{A}$.

Solow (1974) later theoretically demonstrated that even after inclusion of an exhaustible resource, $\boldsymbol{R}$, into the production function that *per capita* output could be maintained indefinitely by substituting capital for natural resources as the latter became depleted stating,

> "presumably the initial [natural resource] stock would be used up early in the game to shore up consumption while a stock of capital is accumulated, which will then be maintained intact while the same level of consumption goes on even after the natural resource pool is all gone" (R. M. Solow, 1974, p. 34)

Further justification of the power of technological advancement seemed to be provided with the publication of *Scarcity and Growth* by Barnett and Morse (1963) in which the authors showed that extraction costs, measured as direct capital and labour inputs per unit of output, of most resources had declined during the first half of the twentieth century, which they attributed to 'self-generating' technological change.

Energy was often assigned a negligible role within economic processes since, "energy's share in total factor cost is small compared to the cost shares of labor and capital" (Lindenberger & Kummel, 2002, p. 101). Some economists have attempted to rectify this situation with the addition of both energy, $\boldsymbol{E}$, and materials, $\boldsymbol{M}$, to produce the so-called ***KLE*** or ***KLEM*** production function (Griffin, 1981; Griffin & Gregory, 1976).

Economic theories generally assume that the market is an ergodic system. Samuelson (1969) claims that this assumption is to take economic from the "realm of genuine history" and ground it in the "realm of science". A number of authors have attempted to study economic systems as non-ergodic, evolutionary systems, most notably Joseph Schumpeter's (1994) analysis of 'creative destruction' in business cycles and John Maynard Keynes', 'General Theory' (1936). Davidson (1996) makes the point that,

> "The possible widespread absence of ergodic conditions in economic phenomena provides a severe limitation on economists' ability to predict and perform vis-a-vis nineteenth-century scientists" (Davidson, 1996, p. 506)

The biophysical systems world view[6]

> "From the biophysical systems perspective, a social system such as an economy is seen in terms of the *physical* activities that take place in it. This is clearly different from the *social* ways in which the activities of society are seen from the political-economic perspective" (J. Peet, 1992, p. 83, emphasis in original)

The biophysical systems perspective stems from the concepts and theories expounded within the physical and life sciences. The biophysical economist believes that the laws of these sciences apply and must constrain the choices available to an economic agent and hence use "basic ecological and thermodynamic principles to analyze the economic process" (Cleveland, 1987, p. 47)

The history of biophysical economics stems back to the eighteenth century French school of economic thought known as the Physicocrats (Dupont & Quesnay, 1768; Mirabeau, 1763; Quesnay, Kuczynski, & Meek, 1972). These economists believed that all economic processes were dependent on a single factor – agriculture - which was subject to objective laws which operated independently of human behaviour. These 'natural laws' had both a physical and a moral component; the physical component including such parameters as soil fertility and rainfall.

The first explicit use of thermodynamic laws to characterise economic processes was made by Podolinsky (1883) which led him to conclude that "ultimate limits to economic growth lay not in the shackles of the relations of production, but in physical and ecological laws" (Cleveland, 1987, p. 52).

[6] This author is indebted to the excellent article *Biophysical Economics: Historical Perspective and Current Research Trends* by Cutler Cleveland.

In the early twentieth century, Nobel laureate Frederick Soddy (1922, 1926) used thermodynamic laws to critique standard, neoclassical economic theory, realising that,

> "life derives the whole of its physical energy or power not from anything self-contained in living matter, and still less from an external deity, but solely from the inanimate world. It is dependent for all the necessities of its physical continuance upon the principles of the steam engine. The principles and ethics of all human conventions must not run counter to those of thermodynamics" (Soddy, 1922, p. 9)

Social scientist Fred Cottrell (Cottrell, 1955) explored the influence of energy use on social development, concluding that the great increases in economic activity seen during industrialisation are due principally to the supplementation of human labour by vast flows of 'surplus energy', normally in the form of fossil fuels.

Ecologist Howard Odum (1977) stressed the importance of energy to all economic activity by arguing that wherever money flows within the economic system there must be a counter-flow of energy to enable the production of goods or services for which the money was exchanged. Odum (Odum, 1975) also developed the energy circuit language (described more fully in Section 0), a means by which to diagrammatically represent energy flows and processes commonly observed in both ecological and social systems.

Odum's theories have received a poor reception from mainstream economists due most notably to his belief in the so-called energy theory of value – that flows of low entropy energy represent the ultimate source of economic value (Cleveland, 1987). However, some of his theories have received at least partial corroboration by subsequent analysis (Costanza, 1980; Liu, Koerwer, Nemoto, & Imura, 2008).

Geologist, Earl Cook (E. F. Cook, 1976) analysed economic processes in terms of three interacting perspectives on economic decision-making. These he termed the *physical*, *social* and *pecuniary* economies (perhaps foreshadowing the development of the weak and strong models of sustainable development). The analysis provided by each of the 'economic' perspectives might provide a different verdict due to the different values and weights placed on various outcomes, for instance, increasing use of the motor car could be seen to have both positive and negative social effects, such as the disruption of the nuclear family due to increased travelling, that would seldom be reflected in a purely monetary analysis. Social views may change over time, such as the view of unemployment as a social evil within our own time, but were viewed as an indication of social progress in Medieval Europe (E. F.

Cook, 1976). Energy analysis would provide the basis of accounting within the physical economic perspective.

Cook furthermore believed that energy from the use of fossil fuels provides the basis of economic growth, such that,

> "With the quality of fossil fuels rapidly diminishing, industrial society has two options. The progress option, as described by Cook, is to go on believing that omnipotent technological change and so-called economic laws will rescue us from any resource-related problems. The prudence option is to accept the fact that physical limits to economic growth do exist and to adjust our values and lifestyles commensurate with energy and resource realities" (Cleveland, 1987, p. 60)

The input-output method of energy analysis was developed at the Energy Research Group (ERG) at the University of Illinois (C. W. Bullard & Herendeen, 1975; B. Hannon, 1975). This method allowed direct and indirect energy costs of any service to be calculated. Hannon (1977) used the results of analysis using the new method to argue for a strong energy conservation policy in the United States.

Another physical scientist, Robert Ayres (Ayres, Kneese, & D'Arge, 1970) used the first law of thermodynamics to critique the standard model of economics (as depicted in Figure 2-9) by arguing that any low entropy resources entering the system must be degraded through consumption and leave as high entropy wastes. Such 'externalities' are symptomatic of all economic activity, not exceptional cases as many economic theorists believed.

Ayres used the second law of thermodynamics to consider the degradation of energy quality due to depletion of energy resources. High quality resources are constituted by stocks of low entropic value which require little energy to discover, extract and process. The depletion of such high quality resources is accelerated by the necessity of using resources that offer lower returns for each unit of energy expended in their retrieval. As such the production of such resources constitutes a "thermodynamic Catch-22" (Cleveland, 1987, p. 62)

In later work Ayres continues to explore the role of both energy and *exergy*[7] in economic growth, using a variant of the production function outlined in the previous section. Ayres et al. (2007) argue that much of the Solow residual can be accounted for by inclusion in the production function of 'useful work' done in the economy by exploitation of energy resources.

[7] Exergy is defined as "the maximum amount of work that can be done by a subsystem as it approaches thermodynamic equilibrium with its surroundings by a sequence of reversible processes" Ayres et al. (2003), p.221

For Nicholas Georgescu-Roegen (1974, 1975), so strong was the connection between entropy and economic process that he called the laws of thermodynamics, especially the second law, "the most economic of all physical laws." Any definition of efficiency of energy use must be defined relative to economic purposes and, as such, thermodynamics is the physics of economic value. By focussing solely on the circular flow of goods and services the standard economic model had lost sight of the importance of availability of low entropy natural resources on which all economic processes are dependent. Unlike Odum, however, Georgescu-Roegen did not believe that all economic value was dependent on such flows, since the ultimate ends of the economic process are not physical, but the life satisfaction enjoyed by members of society.

One-time World Bank economist, Herman Daly, further critiques the standard model of economics by stressing that identifying the circular flow of money within the economy as the source of economic value, represents a case of Whitehead's 'fallacy of misplaced concreteness'.

> "It is, of course, the linear throughput [of matter and energy], not the circular flow of value, that impinges on the environment in the forms of depletion and pollution. It is impossible to study the relation of the economy to the ecosystem in terms of the circular flow model, because the circular flow is an isolated, self-renewing system with no inlets or outlets, no possible points of contact with anything outside itself. Yet in economic theory the circular flow has the spotlight, while the concept of throughput is only dimly visible in the shadows. Consequently, the relation of the economy to its environment is a topic which economic theory has only occasionally illuminated and often obscured"(Daly, 1985, p. 2).

In order to accept the existence of limits to economic growth and throughput of energy and materials, Daly (1977) argues for a steady-state economy in which stocks of capital and population are constant.

Charles Hall, Cutler Cleveland and Robert Kaufmann (1986) together authored *Energy Resource Quality: The Ecology of the Economic Process*, which examines how natural resources are transformed into economic goods and services and analyses the implications of fluctuating energy costs on indicators of economic performance. The authors marry the concepts of 'surplus energy' discussed by Cottrell and of resource quality from the work of Ayres with the concepts of 'net energy yield' and 'energy-return-on-investment' (EROI) from energy analysis.

Costanza and Cleveland (1983) used a net energy approach to assess the ultimately recoverable amount of hydrocarbons in Louisiana. They found a distinctive curve for the EROI of oil and gas as a function of cumulative production of those resources, depicted in Figure 2-10.

Gever et al. (1991) explored the effects of declining domestic oil production on the US economy. The approach argued that standard economic theories cannot be used to predict the implications due to resource depletion since they are built on the assumption that, "production of fuels and other resources is determined solely by conditions within the economy." The authors believed that this condition no longer held; that, "physical changes in the resource base limit US fuel production which in turn influences economic conditions" and that standard economic models could not incorporate these new conditions since "this assumption is antithetical to the philosophy behind "internal" economic models, and hence cannot be built into them *post hoc*"(p. 114).

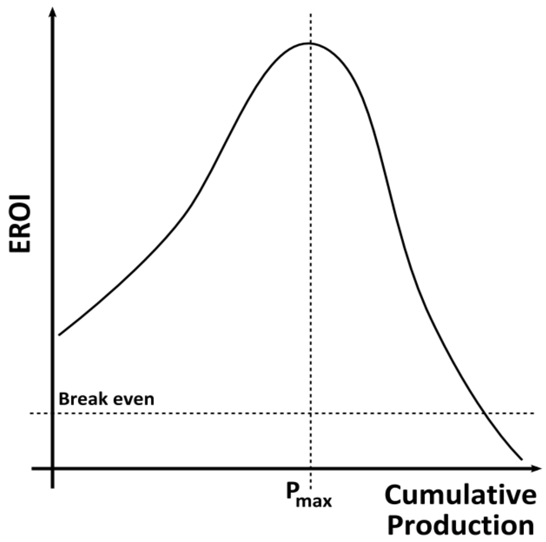


Figure 2-10. EROI as a function of cumulative production[8] adapted from (Costanza & Cleveland, 1983)

Many biophysical economists have highlighted problems with the production function used within neoclassical economics (Cleveland, et al., 1984; Daly & Farley, 2004; Georgescu-Roegen, 1974). The most commonly cited problem being the belief in substitution between factors of production that seemingly violate the laws of thermodynamics, summarised aptly by Ayres and Nair

[8] EROI is a function of cumulative production only in the case of fossil and fissile energy sources. In the case of renewable energy sources, EROI is a function of annual production

> "One can define mass and energy as explicit factors of production, but this does not eliminate the difficulty... [standard KLEM production functions suggest that] one could reduce the input of materials to zero, substitute sufficient capital and labor, and still produce the same quantity of goods. Clearly, this is physically impossible. Both the final goods produced by the economy and the capital stock used to produce them embody a certain amount of mass and energy. Mass and energy cannot be created by labor or capital... Economic theorists, at least briefly, seem to have reinvented the perpetual motion machine..." (Ayres & Nair, 1984, p. 68)

The biophysical systems perspective (as depicted in Figure 2-11) expands the economic world view by including as part of the production of goods and services the raw materials and energy resources upon which it is dependent. The energy transformation sector uses capital from the economy, $\mathbf{S_2}$, in order to extract raw energy resources, **R**, some of which, **D**, are passed back to the main economy and some of which, $\mathbf{S_1}$, are used to operate its internal processes. The net energy yield to the economy is $\mathbf{D} - (\mathbf{S_2} + \mathbf{S_1})$. The ratio $\mathbf{D}/(\mathbf{S_2} + \mathbf{S_1})$ is called the energy-return-on-investment (EROI) and is a measure of the 'accessibility' of the energy resource (Baines & Peet, 1983; P.S. Bodger & Baines, 1988; E. F. Cook, 1976; Charles A.S. Hall, et al., 1986)

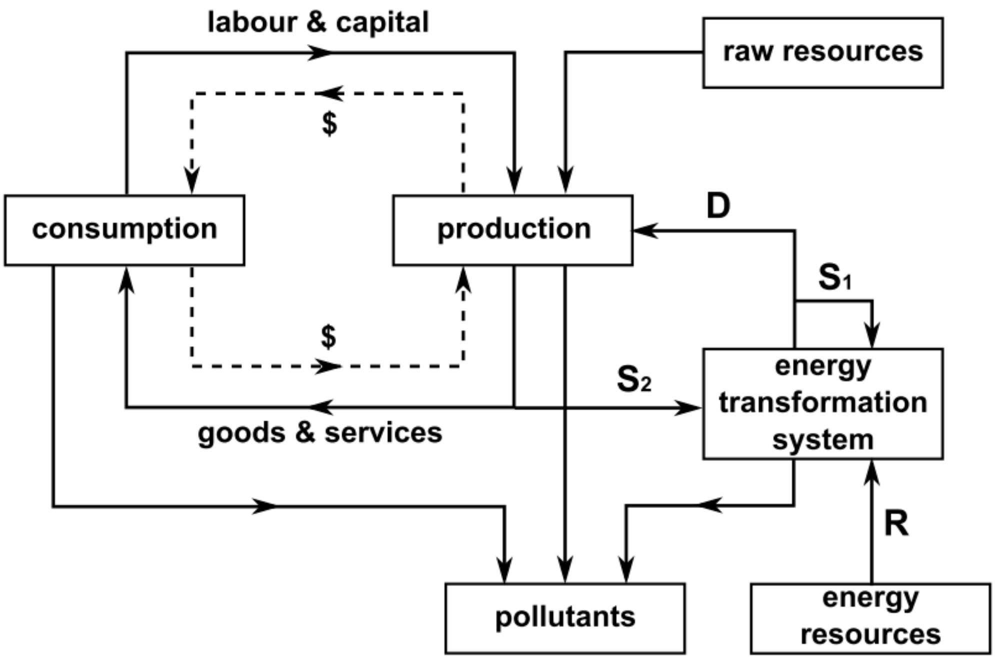


Figure 2-11. The biophysical systems model of the economy from (Gilliland, 1975).
The economy is embedded within an environment from which it obtains energy and raw resources and to which it emits pollutants.

The energy transformation sector, producers and consumers also emit pollutants back into the environment. These pollutants must be effectively assimilated by ecosystem services if they are not to become detrimental to the functioning of the economy.

From this biophysical perspective the economy is seen as an organisationally closed, self-regulating, physically open system, dependent on flows from its environment in order to sustain itself.

2.2. Energy Analysis

Energy analysis is the process of measuring the energy flows through the process or system under investigation. According to Boustead and Hancock "Energy analysis is a technique for examining the way in which energy sources are harnessed to perform useful functions" (Boustead & Hancock, 1979, p. 13). Peet classifies energy analysis as "determination of the amount of primary energy, direct and indirect, that is dissipated in producing a good or service and delivering it to the market" (J. Peet, 1992, p. 87) reflecting the current focus of energy analyses on economic activities.

The techniques of energy analysis have been used by physical scientists and engineers for many hundreds of years, often in the quest for more (energy) efficient machines and processes. Application of the techniques of energy analysis to economic processes stems back to Frederick Soddy (1926). The theme was picked up later by economists such as Nicholas Georgescu-Roegen (1975) and then policy advisors (Gilliland, 1975). More recently attention has expanded to include entire industrial sectors and even whole economies (C. W. Bullard & Herendeen, 1975; Carter, Peet, & Baines, 1980; Costanza, 1978). Of particular importance to energy analysis is investigation of the activities of the energy transformation sector in delivering energy to the rest of the economy. This information is important for a number of reasons. Firstly because of the adverse environmental impacts linked with energy transformation processes, especially of concern recently being the emission of greenhouse gases associated with the combustion of fossil fuels. Secondly, because of the finite availability of fuels and other energy resources, it is important to allocate these resources to activities with a positive net energy return. Thirdly, there is evidence that the quality (i.e. net energy returns) of the major energy sources used by modern, industrial society are declining (Cleveland, 2005), which is of concern, because of the strong link between net energy and the material standard of living and economic opportunity available to a society (Charles A.S. Hall, et al., 1986).

Unlike costs to deliver useful energy considered in purely financial terms, there is an absolute threshold to the energy return of an energy delivery process below which it becomes detrimental to society[9]. This is represented by an EROI = 1, although there is evidence to

[9] This comment has some caveats. There are some boutique applications, such as power for remote systems that may operate with an EROI of lower than one. Such a system essentially acts as a parasite on the rest of the economy. Society may also be willing to accept energy losses for energy in a particular form for special applications, such as fuel for space rockets. The same cannot be the case for those energy systems whose primary function is to deliver energy to the rest of the economy.

suggest that a major energy source must deliver an EROI of better than 3 to be beneficial to society (C. Hall, Balogh, & Murphy, 2009).

System boundary

Energy Analysis has two main methods by which to assess the energy flows through a particular process or product: process analysis or input-output tables.[10] The choice of which method to use is normally made on the basis of where the system boundary is drawn (see Figure 2-12). For any production process, energy inputs may take a number of forms. Perhaps the most obvious is the energy used directly in the process itself, but energy has also been used to extract and deliver the material inputs to the process. The machines involved in the process have also required energy for their manufacture, as have the machines that built those machines, and so on in a regression. If the analyst is interested only in either direct fuel use or the direct material and transport inputs (as represented by levels 1 and 2) then process analysis may be used. If a higher level analysis is required, including material inputs for capital goods and the 'machines to make the machines' then input-output tables must be used. Each level of analysis will reduce the error inherent in the estimate, although, depending on the process involved, a level 2 analysis will generally be accurate to within ± 15% (C. W. Bullard, 1976).

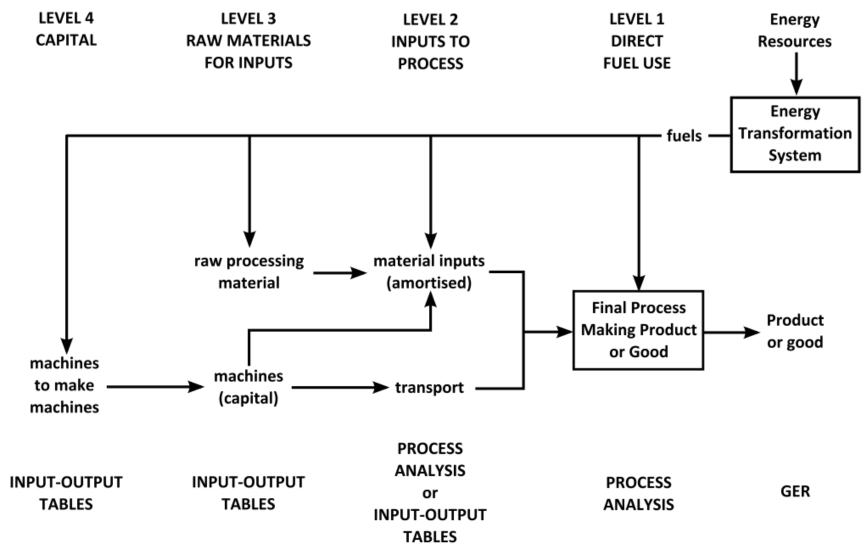


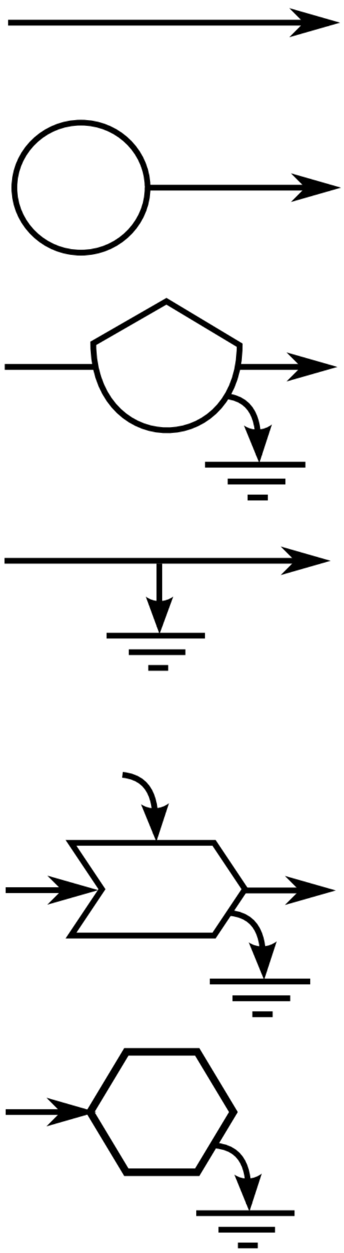
Figure 2-12. Hierarchical levels in energy analysis from (N. J. Peet, 1986).
If only level 1 and 2 inputs to a process are of interest then the analyst may use process analysis, if higher level analysis is required then input-output tables must be used.

[10] Although hybrids between the two methods have also been developed.

2.2.1. Energy circuit language

Renowned ecologist Howard T. Odum developed the energy circuit language as an analogy to electronic circuit wiring diagrams (Odum, 1975). Use of the language ensures that important physical laws, such as those of thermodynamics, are adhered to whilst describing the flow of energy, materials and information through the system being studied (Charles A. S. Hall & Day, 1990). All flows into and out of an element must balance.

The language is based on a series of pictograms, each representing common elements observed within natural and social systems.



Energy circuit

A pathway whose flow is proportional to the quantity in the storage or source upstream

Source

Outside source of energy delivering forces according to a program controlled from outside; a forcing function

Tank

A compartment of energy storage within the system storing a quantity as the balance of inflows and outflows; a state variable

Heat Sink

Dispersion of potential energy into heat that accompanies all real transformation processes and storages; loss of potential energy from further use by the system

Interaction

Interactive intersection of two path-ways coupled to produce an outflow in proportion to a function of both; control action of one flow on another; limiting factor action; work gate;

Consumer

Unit that transforms energy quality, stores it, and feeds it back auto-catalytically to improve inflow

Figure 2-13. Elements of energy circuit language from (Charles A. S. Hall & Day, 1990)

2.2.2. Methodology

This section gives a brief outline of the two methods of energy analysis: process analysis and input-output tables.

Process analysis

Process analysis makes account of all of the material and energy resources used as inputs to a production process, often by splitting the process into various stages, as depicted in Figure 2-14, sometimes referred to a *production modules* (Boustead & Hancock, 1979). Such analysis forms the basis of the Life Cycle Inventory (LCI) methodology (Bauman & Tillman, 2004).

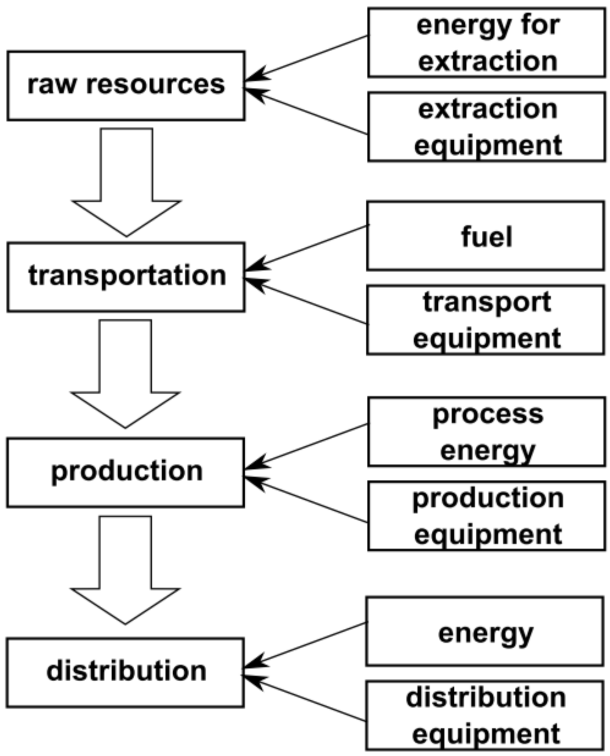


Figure 2-14. Energy analysis of theoretical industrial process.
Energy and capital inputs are analysed at each stage of the process: extraction of raw resources, transportation of materials, production and distribution of final product.

Input-output analysis

Input-output energy analysis builds directly upon economic input-output analysis using monetary exchanges as a proxy for energetic exchanges. The energy intensity, often expressed in megajoules per dollar (MJ/$) of each economic sector is used to convert monetary flows between the various sectors into flows of energy (N. J. Peet, 1986).

Applying an energy balance to the economic sector $\boldsymbol{j}$ (as depicted in Figure 2-15) entails assuming that energy embodied in the inputs to sector $\boldsymbol{j}$ from sector $\boldsymbol{i}$, $\boldsymbol{x_{ij}}$, plus the energy burned in sector $\boldsymbol{j}$ is passed on as part of the outputs of that sector, $\boldsymbol{x_j}$. This generates a set of n equations (for each of the n sectors) that may then be solved to find the embodied energy intensity per unit of output, $\boldsymbol{\varepsilon_j}$. $\boldsymbol{E_j}$ represents the energy extracted from the Earth by sector $\boldsymbol{j}$ which is non-zero only for primary energy sectors.

The units of transactions, $\boldsymbol{x_{ij}}$, is often mixed between physical and monetary units depending on what is available to the analyst (N. J. Peet, 1986). The total energy embodied in the outputs of sector $\boldsymbol{j}$ is thus:

$$\sum_{i=1}^{n} \varepsilon_i A_{ij} x_{ij} + E_j = \varepsilon_j x_j \qquad [2\text{-}2]$$

$\boldsymbol{A_{ij}}$, represents the amount of product $\boldsymbol{i}$ needed to produce a unit of product $\boldsymbol{j}$. When written in matrix notation this equation becomes:

$$\varepsilon A + E = X \qquad [2\text{-}3]$$

$\boldsymbol{X}$ is the diagonalised matrix of sector outputs. This formulation may be rearranged to solve for the energy intensity, $\boldsymbol{\varepsilon}$ in terms of $\boldsymbol{e}$, a unit vector that defines the energy cost of goods and services; $\boldsymbol{I}$ is the identity matrix:

$$\varepsilon = e(I - A)^{-1} \qquad [2\text{-}4]$$

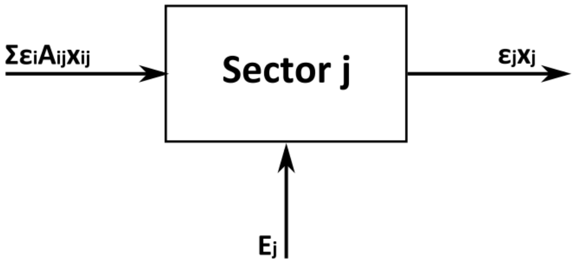


Figure 2-15. Energy flows into and out of an economic sector j from (N. J. Peet, 1986). All flows must balance in accordance with thermodynamic laws

2.2.3. Net energy and energy-return-on-investment

> "Whenever man can recover more useful energy or work from any part of the natural energy system than he has to expend to recover it, he is the beneficiary of a *natural subsidy*." (E. F. Cook, 1976, p. 19)

When considering the purpose of the energy transformation system, it is clear that the system must deliver an energy surplus to the main economy, over and above the energy requirements of that sector. An energy sector that only delivered as much energy as required for it to operate would be of little benefit to society. Such surplus is termed *net energy yield* and is defined as "the amount of energy delivered into the mainstream of economic activity less the amount which is required to bring it there" (N. J. Peet, 1986, p. 16). In terms of Figure 2-16 net energy yield, **N**, is the energy delivered to the economy by the energy sector, **D**, less two 'subsidies': the operating energy of the energy sector, $\mathbf{S_1}$, and the energy embodied as capital required by the energy sector, $\mathbf{S_2}$; that is $\mathbf{N} = \mathbf{D} - (\mathbf{S_1} + \mathbf{S_2})$.

Another important measure of the usefulness of a particular energy resource or technology is the ratio of the energy delivered by that technology, **D**, to the total energy 'subsidies' ($\mathbf{S_1} + \mathbf{S_2}$), known variously as the energy-return-on-investment (EROI), the energy-return-on-energy-invested (EROEI), the energy yield ratio (EYR) and the energy payback ratio (EPR). This ratio measures the accessibility of a particular resource and can be used as a means of comparing various technologies to decide on the effectiveness of applying energy resources; especially useful in energy policy.

2.2.4. Theoretical vs. empirical studies

Theoretical energy analyses are often carried out on systems that are yet to be built (S. W White, 1998) or on technologies that are still in the development phase (Carlson, 1979). Such studies display a higher degree of uncertainty than those analyses carried out on existing systems using empirical data.

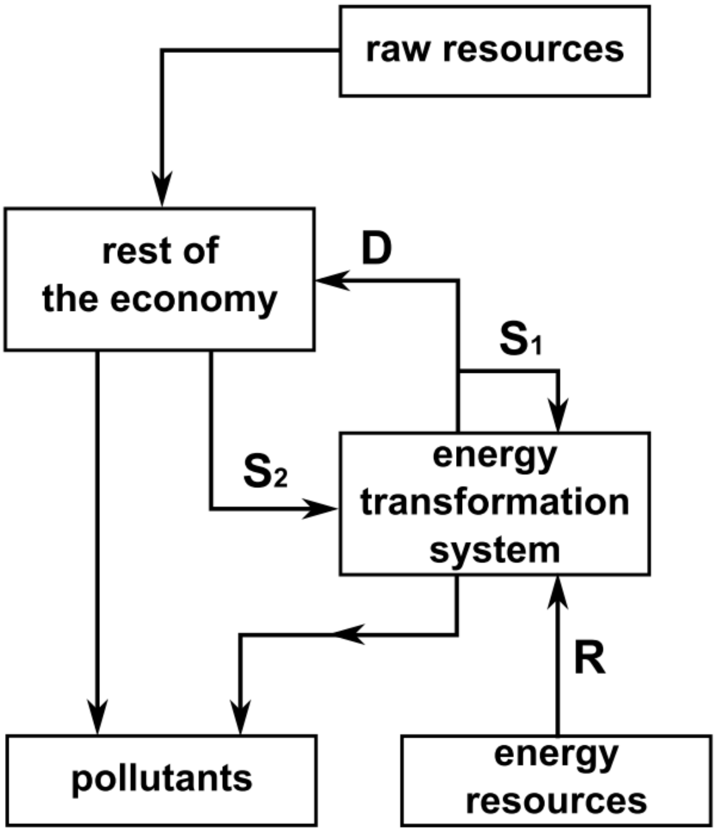


Figure 2-16. Relationship between energy transformation system and the rest of the economy

2.3. Modelling systems

> "The art of modelling, like the arts of poetry writing or architecture or engineering design, is to include just what is necessary to achieve the purpose, and no more." (D. H. Meadows, et al., 1992, p. 108)

2.3.1. What are models?

In its most basic form, a model is "any simplified representation of reality" (D. H. Meadows, et al., 1992, p. 105). In truth, all of our conceptions about reality and the language we use to communicate them are also mental models; inexact symbols attempting to capture some facet of the vastly complex phenomena to which they refer. Indeed our concept of "reality" itself is a vastly simplified mental model which each of us carries around with us; what psychologists refer to as the "belief schema" (Tedeschi & Calhoun, 1995). Indeed as Meadows et al. point out, "human mental models must be ludicrously simple compared with the immense, complex, ever-changing universe within which they exist" (D. H. Meadows, et al., 1992, p. 105).

In this sense, then, mental models mediate between human cognition and phenomena (Fishwick, 2007) and are vital to theory construction in science (Morgan & Morrison, 1999). The power of these models is their ability to explain some aspect of our universe. Newton's theory of gravity is a model that reduces objects to point masses in an attempt to explain their motions. The appeal of these explanations is their (relative) simplicity.

What are now more commonly thought of as models, are structures that represent "the formalization of our knowledge about a system" (Charles A. S. Hall & Day, 1990, p. 8) and, as such, are often presented in the formal languages of science or mathematics. Such formalisation enables the predictive power of the model to be exploited, through the execution of a numerical model upon a computer, for instance.

Any classification of some aspect of reality as a system constitutes the construction of a model. Hereafter, a distinction is made between elements within the system under exploration and elements within the model attempting to explore that system (i.e. between the mental model of the author and the formal model constructed) by capitalisation of the latter, for instance the system element 'net energy yield' of the global energy-economy system shall be represented by the model element, NET ENERGY YIELD.

2.3.2. The purpose of models

The primary aim of modelling is the attempt to predict future outcomes based on past behaviour; "modelling is done to aid the conceptualization and measurement of complex systems and, sometimes, to predict the consequences of an action that would be expensive, difficult, or destructive to do with the real system" (Charles A. S. Hall & Day, 1990, p. 8). Meadows (2007) identifies a number of purposes for prediction:

- **prediction for the purpose of entertainment**, such as predicting the outcome of a football match;
- **defensive predictions**, wherein it is assumed that the antecedent conditions cannot be affected but that a series of adjustments might create a more favourable outcome, such as raising levees to protect against flooding and;
- **pro-active predictions**, where-in the purpose is to pre-empt the outcome by changing the antecedent conditions, such as giving up smoking to reduce the risk of lung cancer.[11]

The purpose of the model will then play a large part in determining its structure, for instance a model constructed for the purposes of *defensive prediction* may be unsuitable for the purpose of *pro-active prediction* such as investigating policy options (D. L. Meadows, 2007).

2.3.3. The modelling process

Hannon and Ruth (2000) characterise the modelling process as an iterative loop (see Figure 2-17). Real events inspire their description in abstract terms. This is the construction of a mental model – the characterisation of the system. The model is then formalised to allow the modeller to form relevant conclusions and possibly to make predictions (and appropriate responses) which may then impact on real events. The process is iterative since the impact of the model's construction on real events may then inspire the development of the model or the creation of a different model.

[11] Such 'pro-active prediction' are often (though obviously not always) invalidated by the prophylactic measures taken in response to them.

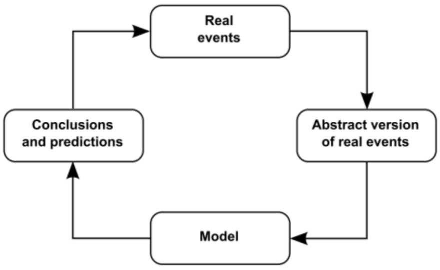


Figure 2-17. A diagrammatic representation of the iterative process of modelling real world phenomena from (B. M. Hannon & Ruth, 2000).
Real events inspire their description in abstract terms (as a system or mental model). The model is then formalised in order to form conclusion and possibly to make predictions which may then impact on real events.

Hall and Day (1990) offer a more detailed description of the modelling process (as represented in Figure 2-18). The process begins with the identification of the (natural and/or social) system to be studied and the formulation of an appropriate 'simulation problem'. Knowledge is then gained about the system, through either a literature review or direct observation, in order to generate a set of assumptions pertinent to the resolution of the simulation problem. A formal model of the system is constructed and the results and predictions are validated leading either to new knowledge about the system and resolution of the initial problem, or redefinition of the problem and generation of a changed set of assumptions entailing the construction of a new model with different results

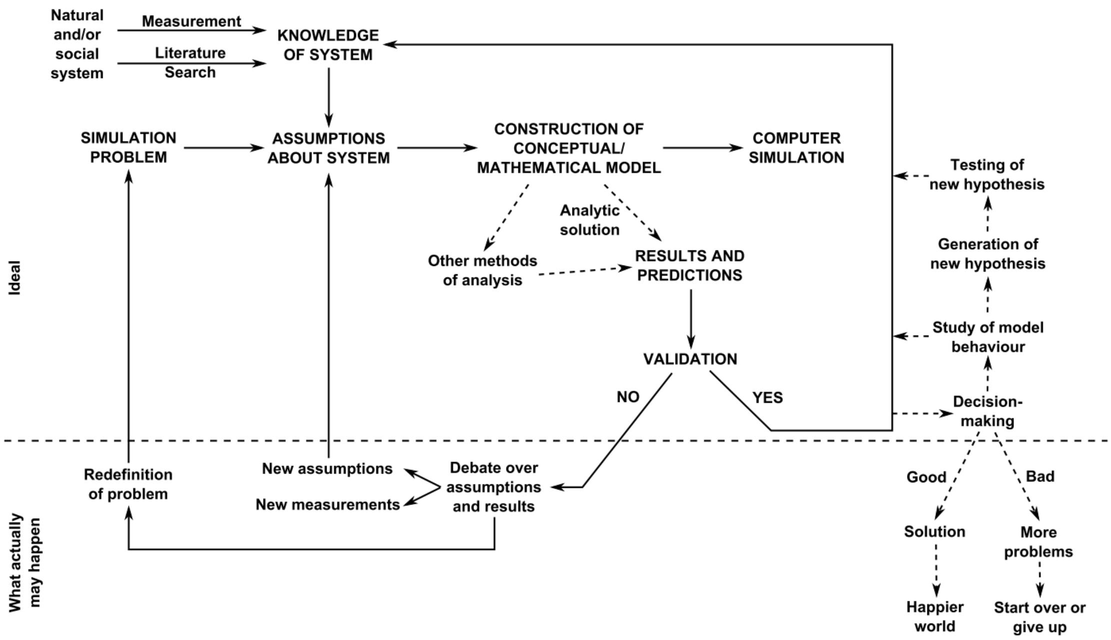


Figure 2-18. A schematic representation of the model-building process from (Charles A. S. Hall & Day, 1990).
The system to be studied is identified and the 'simulation problem' is formulated. Knowledge of the system is gained to generate a set of assumptions pertinent to the resolution of the simulation problem. The model is constructed and the results are validated leading either to resolution of the initial problem, or redefinition of the problem and the generation of a changed set of assumptions leading to the construction of a new model with different results.

Hannon and Ruth (2000) outline some general Principles of Modelling; a number of steps that facilitate the modelling process:

1. Define the problems and goals of the model.
2. Designate the state (stock) variables.
3. Select the control (flow) variables.
4. Select the parameters for the control variables.
5. Examine the resulting model for violations of physical or economic laws
6. Choose the time horizon.
7. Run the model and check the results.
8. Vary the parameters to reasonable extremes to see if the results still make sense.
9. Compare the results with experimental data.
10. Revise the parameters and, perhaps, even the model.

These steps form the basis of the methodology followed in the construction of the GEMBA model.

2.3.4. Numerical simulation vs. analytical solutions

According to Hall and Day, "the analytic approach refers to a mathematical set of procedures for finding exact solutions to differential and other equations" (Charles A. S. Hall & Day, 1990, p. 9). As Forrester remarks "Because the analytic solution of system behavior is so informative and because it allows direct computation of the system condition at any specified time, one might presume that an analytical solution should always be obtained in every system study." However, as he goes on to state,

> "most dynamic behavior in social systems can only be represented by models that are nonlinear and so complex that analytical mathematical solutions are impossible. For such systems, only the simulation process using step-by-step numerical solution is available" (Forrester, 1972, pp. 3-10).

Hall and Day (1990) offer a classification of mathematical problems and their ease of solution via various analytic methods: algebraic, ordinary- and partial-differential equations (see Table 2-2). An increase in complexity of mathematical problems, due either to their consisting of non-linear or multiple equations, quickly leads to their being impossible to solve via existing analytic methods. Such problems may only be solved via numerical solution.

A corollary of this insight is that insistence on an analytical solution to a model severely limits the complexity, and hence applicability, of the model to real systems.

Table 2-2. Classification of mathematical problems and their ease of solution by analytical methods from (Charles A. S. Hall & Day, 1990).
An increase in complexity of mathematical problems, due either to their consisting of non-linear or multiple equations, quickly leads to their being impossible to solve via analytic methods. Such problems may only be solved via numerical solution.

	Linear Equations			**Nonlinear Equations**		
	One equation	Several equations	Many equations	One equation	Several equations	Many equations
Algebraic	Trivial	Easy	Essentially impossible	Very difficult	Very difficult	Impossible
Ordinary differential	Easy	Difficult	Essentially impossible	Very difficult	Impossible	Impossible
Partial differential	Difficult	Essentially impossible	Impossible	Impossible	Impossible	Impossible

CHAPTER 3. GLOBAL ENERGY SUPPLY MODELLING

Our ability to harness natural flows of energy and direct them to our own use is vital to the development of our technological, social, economic systems and, even, culture itself (L. A. White, 1943). Given this importance, many researchers have investigated the nature of regional and global energy systems to try and understand its dynamic nature and its interactions with the other sectors of the economy which are dependent upon it.

In his essay *The Future of Energy*, Clark C. Abt (2002) summarises his thirty-five year review of long-range (ten- to twenty-year) energy forecasts by identifying the following features:

1. Mainly economic and technological forecasting, by economists and technologists. Almost no social, political, or military forecasting of events or trends affecting energy demand.
2. Emphasis on demand and consumption forecasting, including the most energy-consuming technologies of manufacturing, housing, and transportation. Implicit assumption that market forces will always (and promptly!) generate enough supply to meet demand.
3. The spread of macroeconometric modeling methodology from university departments of economics to government and industry think tanks and independent research organizations, mostly in the United States but also in Europe and Japan.
4. The spread of mathematical process modeling prom systems engineering through engineering project management (PERT – Program Evaluation and Review Technique) into Forrester's Industrial Dynamics. This was combined with mathematical optimization techniques of Linear Programming and Dynamic Programming, developed originally in military operations research, into “world modelling” for longer-range economic and natural resources forecasting (D. H.

Meadows, et al., 1972). This approach has since been discredited as the resource depletion hypothesis proved untenable in the face of substitutes, but may be revived in more inter-disciplinarily sophisticated forms by the growing awareness of global environmental constraints.

5. Thus far, attempts to extend short-term econometric modeling methods to long-term and multi-disciplinary forecasting (including social, political, cultural, and technological forecasting) have not been successful. Macroeconomic growth models, barely better than random in their two-year projections when there are no major disasters or structural changes, continue to be inappropriately extended to five- to twenty-year projections (as in DOE's 2020 energy forecast). These are usually too narrow and inaccurate to be of much use and are inferior to expert judgement."

This chapter gives a brief account of the many varied attempts that have been made in this field focussing specifically on those models that look at the global energy system (see Jebaraj and Iniyan (2006) for a more detailed review across all levels and specific applications).

The various models have been divided into three categories to capture the aims and intentions driving the formulation of the various models. The first group includes those modellers who have attempted to capture the growth of the energy system using various curves (most commonly some variation on the logistic growth curve) in an attempt to forecast future states of the system.

The second group includes the many models that have been produced to investigate the dynamic interaction between economic growth due to population growth and rising living standards (entailing an attendant increase in energy demand) and the available energy supply technologies, with the objective of minimising the future cost of energy supply. These models often have the intention of influencing energy planning policy and financial investment.

The third group of models has been produced by those modellers using biophysical relationships as primary determinants of economic activities. Such models often characterise growth of the economic system in terms of the supply of natural and energy resources (especially fossil fuels).

3.1. Deterministic models using growth curves

This group of models consists of those that attempt to predict future energy supply by fitting various growth curves to historic data. Such models perceive the energy-economy system as an open-loop system whose behaviour may be captured using analytic techniques. The two main exponents of this method are the (in)famous projections of U.S. and world oil production by M. King Hubbert (1956) using logistic growth curves and the energy market substitution curves of Cesare Marchetti (1977). Other examples of such models will also be given a brief description.

3.1.1. Hubbert production cycle

In 1956 M.K. Hubbert presented a seminal paper at the Spring Meeting of the Southern District Division of Production, American Petroleum Institute (Hubbert, 1956). This paper outlined what he called the 'production cycle' for exhaustible resources, in which annual production increases, often at an exponential rate, before passing a point of inflection, whereupon the rate of increase diminishes until the production reaches a maximum peak in production (Hubbert's Peak) before subsequently declining (see Figure 3-1). The area under the curve represents cumulative production; hence in Figure 3-1 each square represents 5 units of production and the total production is 100 units.

Hubbert modelled these production curves using a logistic growth curve for cumulative production $\boldsymbol{P}$, which increases exponentially at rate $\boldsymbol{r}$, up to some limit $\boldsymbol{K}$, defined by the ultimately recoverable resources of the energy source (see Figure 3-2).

Such logistic curves are defined as a function of time by the equation:

$$P(t) = \frac{KP_0 e^{r(t-t_0)}}{K+P_0(e^{r(t-t_0)}-1)} \qquad [3\text{-}1]$$

The production rate, $\dot{\boldsymbol{P}}$, may be calculated by differentiation of $\boldsymbol{P}$ with respect to time to obtain:

$$\dot{P} = \frac{d}{dt}P(t) = rP\left(1-\frac{P}{K}\right) \qquad [3\text{-}2]$$

Taking the ratio of the rate of production to cumulative production, $\dot{\boldsymbol{P}}/\boldsymbol{P}$, gives a form which, if plotted as a function of cumulative production, is linear, intercepting the vertical axis at $\boldsymbol{r}$ and the horizontal axis at $\boldsymbol{K}$ (see Figure 3-3).

$$\frac{\dot{P}}{P} = \frac{rP}{P}\left(1-\frac{P}{K}\right) = r\left(1-\frac{P}{K}\right) \qquad [3\text{-}3]$$

Plotting historical data in this form (as the ratio of rate of production to cumulative production as a function of cumulative production) allows estimation of ***r*** and ***K*** for existing energy resources and the generation of subsequent production curves (see Figure 3-4).

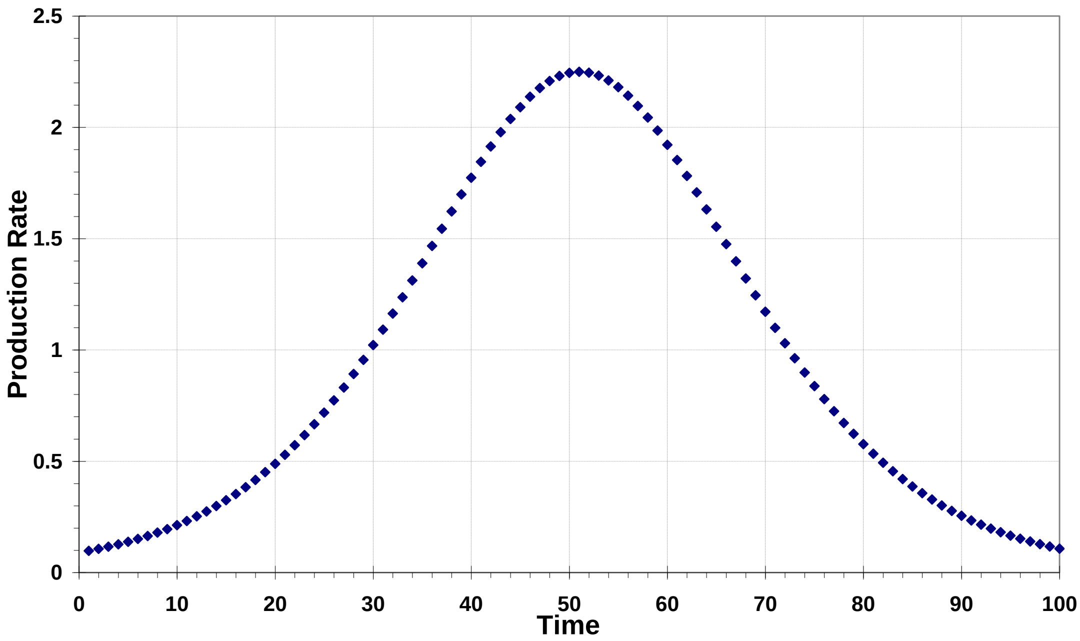


Figure 3-1. Hubbert's production cycle generated using a logistic growth model.
Energy production increases exponentially through time before peaking and decreasing. The area under the curve represents cumulative production with each square representing 5 units of production for a total of 100 units.

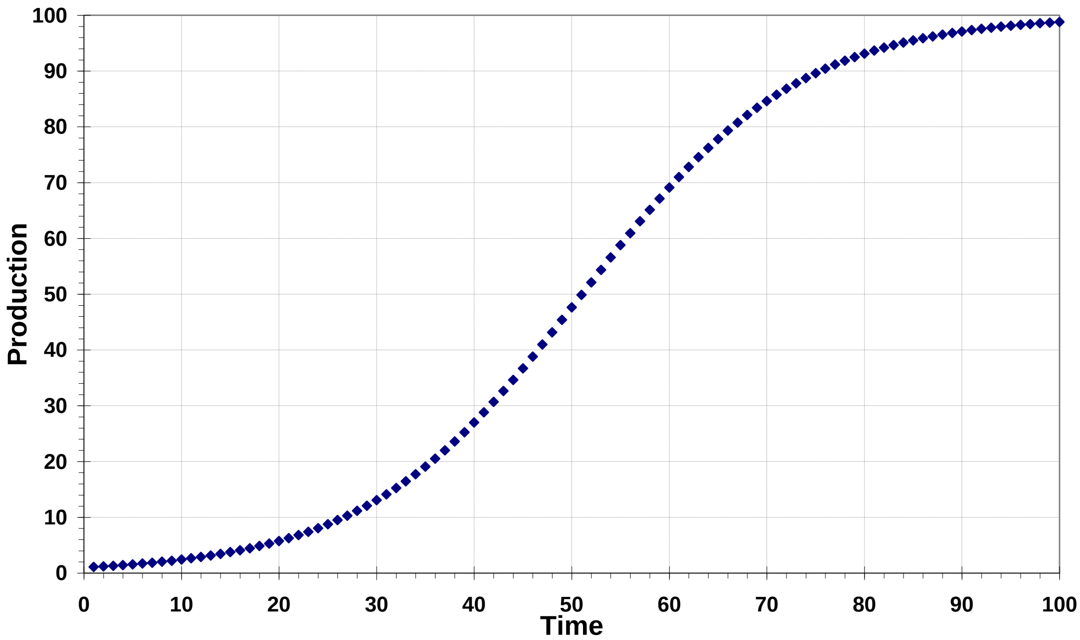


Figure 3-2. Logistic growth of production at rate r = 0.09, up to limit K = 100.
Production initially increases exponentially before passing through a point of inflection at time = 50 and subsequently slowing up to the limit.

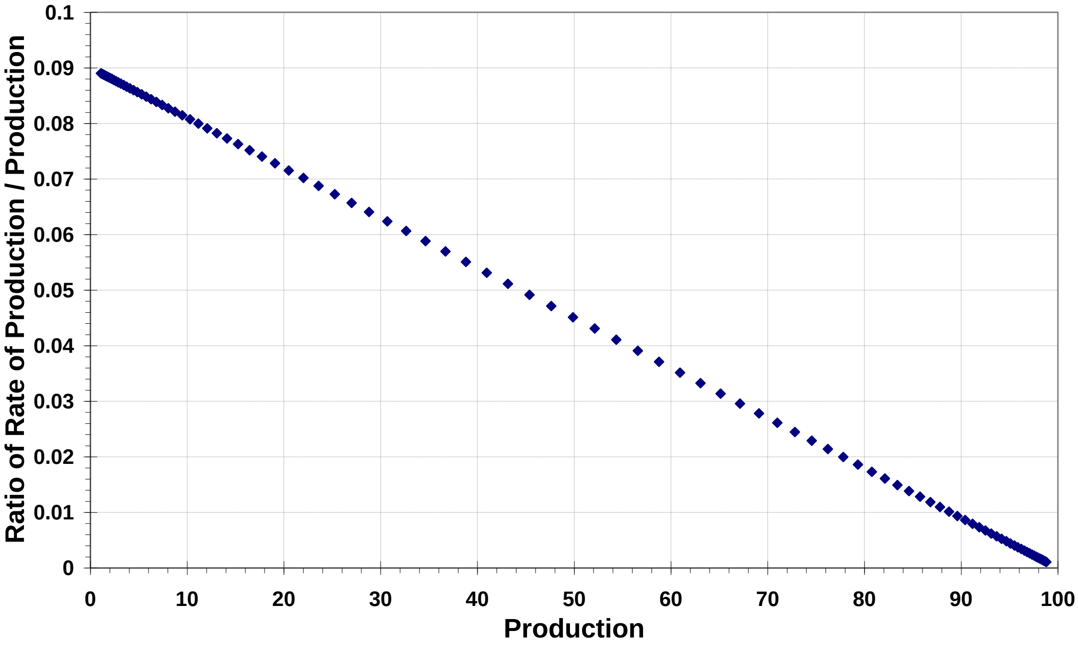


Figure 3-3. Linearisation of logistic growth model.
The ratio of the rate of production to cumulative production is plotted as a function of cumulative production. The resultant function intercepts the vertical axis at *r* and the horizontal axis at *K*.

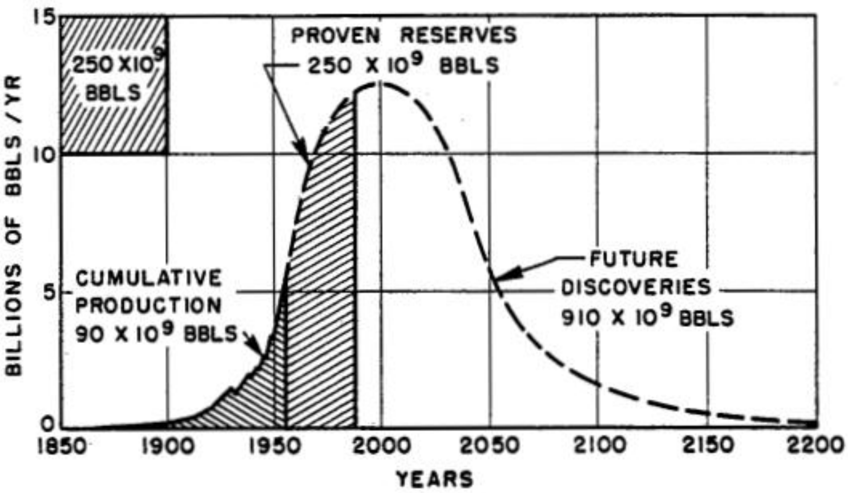


Figure 3-4 Hubbert's projections of ultimate world crude-oil production.
This projection is based upon initial resources of 1250 billion barrels, whereas many estimates now put the value of ultimately recoverable resources (URR) at around 2000 billion barrels. Note the peak in production around the year 2000 at a rate of around 12.5 billion barrels per year, a rate far below the 2007 production rate of 31 billion barrels per year (BP, 2008).[12]

[12] A barrel of oil equivalent (boe) is a unit of energy equal to 6.1 GJ, hence oil reserves of 1250 Gboe is around 7625 EJ, Hubbert's projection of annual oil production of 12.5 Gboe/yr amounts to 76 EJ/yr and current production of 31 Gboe/yr is equal to 189 EJ/yr.

Utilisation of the linearisation technique and finding 'best-fit' curves for both annual and cumulative production data has allowed the generation of a number of projections for each of the non-renewable energy sources (for a full explication of the method used see Appendix D). There is a wide range in the production curves produced under different circumstances suggesting that the technique is very susceptible to changes in initial assumptions.

Table 3-1. Summary of logistic growth curves under various 'best-fit' procedures.
The method offers little guarantee of consistency when fitting curves to either 'linearised', cumulative or annual production data.

	r	K (EJ)	P_0 (EJ)	t_0	Peak Year	Peak Production (EJ/yr)
Coal						
Linear Regression						
1867-2007	0.0399	8000	4	1800	1990	80
1913-2007	0.0280	13500	37	1800	2010	95
1938-2000	0.0209	39300	109	1800	2081	205
1938-2007	0.0205	53400	111	1800	2101	274
Fit Cumulative Production	0.0292	11844	33	1800	2001	86
Fit Annual Production						
Historic data	0.0200	48263	128	1800	2097	241
IEA projections	0.0330	30000	7	1800	2055	247
Historic + IEA[13]	0.0200	187092	115	1800	2169	937
MEAN	**0.0264**	**48925**	**68**	**1800**	**2063**	**271**
RANGE	**0.0199**	**179092**	**124**	**0**	**179**	**857**
Oil						
Linear Regression						
1860-2007	0.1182	6100	1E-3	1860	1991	180
1965-2007	0.0739	8800	0.4	1860	1994	163
1985-2007	0.0478	14300	12	1860	2008	171
Fit Cumulative Production	0.0707	8950	0.8	1860	1992	158
Fit Annual Production						
Historic data	0.0589	11069	3	1860	1999	163
IEA projections	0.0292	29954	26	1860	2041	219
Historic + IEA[14]	0.0348	24767	7	1860	2035	215
MEAN	**0.0619**	**14849**	**7**	**1860**	**2008**	**181**
RANGE	**0.0890**	**23854**	**26**	**0**	**50**	**61**

[13] In this case the 'best fit' curve was constrained by having to pass through both the first and last years of IEA projections (2008 and 2030). If this constraint was removed the value of K obtained was of the order of 10^{12} EJ.
[14] In this case the 'best fit' curve was constrained by having to pass through both the first and last years of IEA projections (2008 and 2030). If this constraint was removed the value of K obtained was of the order of 10^{12} EJ.

	r	K (EJ)	P_0 (EJ)	t_0	Peak Year	Peak Production (EJ/yr)
Gas						
Linear Regression						
1880-2007	0.0993	3500	0.03	1880	1997	87
1970-2007	0.0718	5400	0.8	1880	2003	97
1990-2007	0.0594	7500	3	1880	2011	111
Fit Cumulative Production	0.0734	5070	0.7	1880	2000	93
Fit Annual Production						
Historic data	0.0619	6894	2	1880	2009	107
IEA projections	0.0170	146652	208	1880	2186	622
Historic + IEA	0.0469	11994	0.3	1880	2028	141
MEAN	**0.0614**	**26716**	**31**	**1880**	**2033**	**180**
RANGE	**0.0823**	**143152**	**208**	**0**	**189**	**535**
All Fossil Fuels						
Linear Regression						
1970-2006	0.0442	33300	3	1800	2009	369
Fit Cumulative Production	0.0349	78596	256	1800	2044	686
Fit Annual Production						
Historic data	0.0416	39385	138	1800	2016	410
IEA projections	0.0489	45495	0.6	1800	2030	557
Historic + IEA	0.0346	66143	17	1800	2039	573
MEAN	**0.0408**	**52584**	**83**	**1800**	**2028**	**519**
RANGE	**0.0143**	**45296**	**255**	**0**	**35**	**317**
Nuclear						
Linear Regression						
1975-2007	0.1800	230	0.2	1960	1998	10
1985-2007	0.1452	270	0.9	1960	1999	10
1995-2007	0.1041	370	4	1960	2003	10
Fit Cumulative Production	0.0811	9248	6	1960	2051	187
Fit Annual Production						
Historic data	0.0516	9248	22	1960	2077	119
IEA projections	0.0126	9296	527	1960	2183	29
Historic + IEA	0.0642	772	16	1960	2019	12
MEAN	**0.0913**	**4205**	**82.3**	**1960**	**2047.14286**	**54**
RANGE	**0.1674**	**9066**	**526.8**	**0**	**185**	**177**
Fossil & Fissile						
Linear Regression						
1970-2006	0.0441	34500	3	1800	2010	380
Fit Cumulative Production	0.0354	73465	15	1800	2041	650
Fit Annual Production						
Historic data	0.0419	40395	5	1800	2016	423
IEA projections	0.0251	108368	145	1800	2063	681
Historic + IEA	0.0346	66143	17	1800	2039	573
MEAN	**0.0362**	**64574**	**37**	**1800**	**2034**	**541**
RANGE	**0.0190**	**73868**	**142**	**0**	**53**	**301**

3.1.2. Marchetti substitution model

Building on Fisher and Pry's (1971) investigations of market penetration by new technologies, Marchetti (1977) modelled the energy system as a sequence of the introduction and subsequent domination of market share by new technological innovations over very long time scales. The sequence begins with biomass and farm waste, then coal, oil and gas, then nuclear generation, with some combination of solar and fusion ('solfus') assumed to dominate in the future. Total energy production was assumed to continue at the historical rate of 2% increase per year. The evolution of the system was predetermined by the timely arrival of new technologies as if "the system has a schedule, a will, and a clock"(Marchetti, Nakicenovic, Peterka, & Fleck, 1978).

According to Fisher and Pry (1971), the rate, dF/dt, at which an incoming technology penetrates the market is proportional to the portion of the market not yet exploited (1 – F):

$$\frac{1}{F}\frac{dF}{dt} = \propto (1 - F) \qquad [3\text{-}4]$$

This formulation may be re-arranged to obtain:

$$ln\left(\frac{F}{1 - F}\right) = \propto t + C \qquad [3\text{-}5]$$

Thus, the incoming technology's market penetration forms a straight line on a log-plot over time. In Marchetti's model, this is supplemented by an assumption that all incoming technologies, after a period of market domination undergo a subsequent decline in market share before dropping out of the market on a "first in – first out" basis as depicted in Figure 3-5.

Accordingly, substitution between energy sources occurs on a perfectly pre-determined basis (assuming the timely introduction of a new technology) and has nothing whatever to do with the exhaustion of a resource. This assumes that resources of a particular energy source are enough to provide the production predicted by the model. Such issues occurred to Marchetti, causing him to remark, "I did this exercise and discovered that the world will not be short of oil, whether nuclear energy will keep the present rate of penetration and perhaps even if not, but that there may be problems with [supplies of] natural gas"(Marchetti, 1977). As can be seen from Figure 3-5, natural gas has indeed been produced in smaller amount than predicted by the model (the shortfall being made up by greater production of coal and oil) perhaps vindicating Marchetti's remarks.

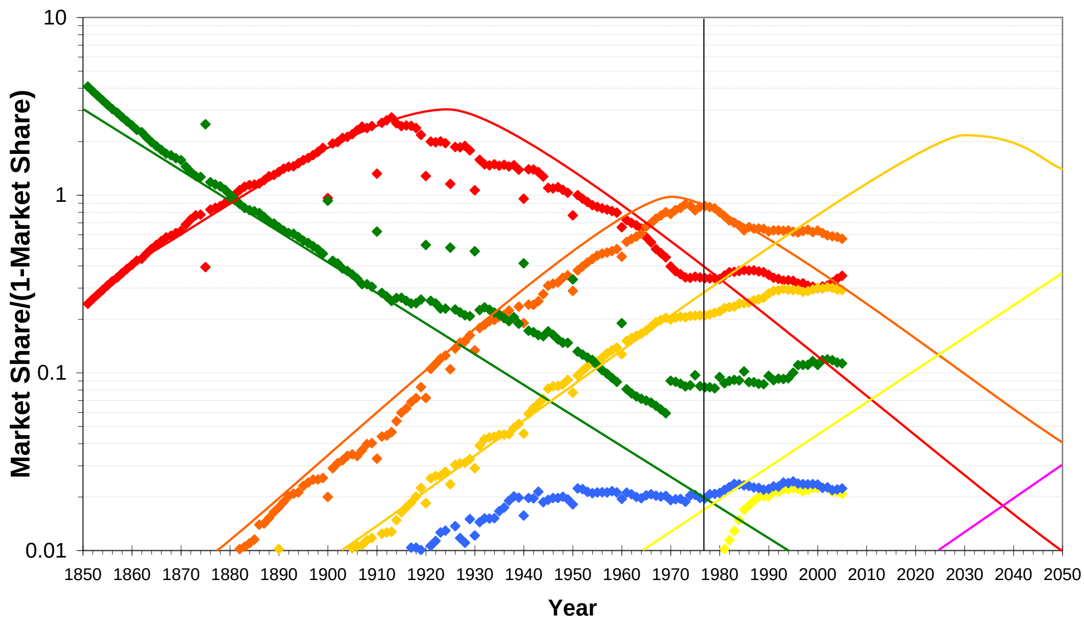


Figure 3-5. Marchetti's curves for substitution between primary energy sources for the world. Dots are historic production data, lines are the model; red is coal, green is biomass, orange is oil, gold is natural gas, yellow is nuclear and pink is the future unknown technology "solfus", presumably standing for 'SOLar and/or FUSion'. Marchetti's model ignores hydro (shown in blue) despite the contribution of hydro being at least as large as nuclear and for a much longer period of time. The vertical black line shows the year of Marchetti's publication. As can be seen, coal and oil have both been produced in greater amounts than Marchetti's projections and natural gas has been produced in a lesser amount.

3.1.3. Other growth models

Zerta et al. (2008) attempted to predict the state of the global energy market to 2100 (as an alternative to the IEA World Energy Outlook 2006) by assuming that declining fossil fuel production (modelled using Hubbert's technique) would be somewhat offset by growth in renewable energy sources, modelled using logistic growth curves at current rates up to the limit set by their technical potentials (see Table 3-2 for details).

One problem with such an approach, as noted in the Introduction (see Section 1.1.1), is that production from energy sources tends to undergo rapid growth during the early stages of production, thereafter slowing to a lower rate of growth. If growth rates of such immature technologies as wind, solar and geothermal are extrapolated as indicative of later growth, estimated production is likely to be larger than the energy source might actually deliver.

Other authors to have used growth curves include Devezas et al. (2008) in an update to Marchetti's method, and Tunji (1986) in a review of such growth curves to estimate world primary energy consumption.

Such growth models constitute an analytic approach to energy modelling, since energy production is a function of time as the independent variable. Their power lies in their simplicity and that the state of the system is known for any specified time. The underlying assumption about the energy system, however, is that the system has an open-loop structure with no feedback.

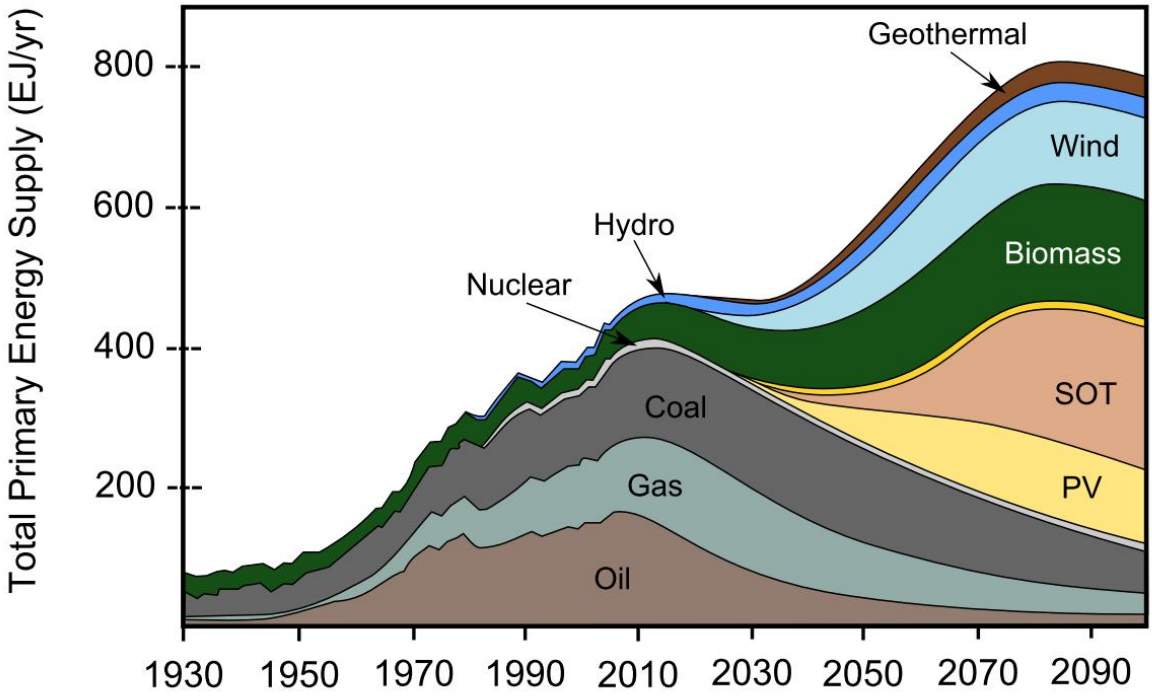


Figure 3-6. Projection of total primary energy supply to 2100 with data from (Zerta, et al., 2008)

Table 3-2. Assumptions underpinning Zerta et al. growth model

Renewable Energy Source	Technical Potential (TWh(e)/yr)	Technical Potential (EJ(e)/yr)	Production		Average annual growth (% p.a.)
			2005	2030	
Biomass			1032 Mtoe	1650 Mtoe	1.9
Hydropower	13 000	43.2	2831 TWh	4970 TWh	2.3
Geothermal	15 000	54			
electricity			56.8 TWh	676 TWh	10.5
heat			2.1 Mtoe	31 Mtoe	11.3
Wind	60 000	216	121 TWh	3742 TWh	16
PV	25 000	90	4.9 TWh	1147 TWh	19
SOT	64 000	230.4	0.7 TWh	456 TWh	30

3.2. Energy-economy optimisation

The next group of energy models attempt to capture the dynamic interaction between the various technologies (and associated costs) comprised of the energy sector and the demand for energy from the rest of the economy due to various factors, such as population growth and increasing living standards.

These models are more sophisticated than the analytic models discussed in the previous section. They characterise the energy sector as being made up of a chain of technologies delivering energy from raw resources to meet energy demand within the economy (as depicted in Figure 3-7). The combination of technologies delivering a range of energy resources to supply a variety of energy demands constitutes the Reference Energy System (RES). Energy flows through the energy sector to the main economy in exchange for money, some of which is re-invested back into the energy sector.

Some models have attempted to capture this complexity within a single model (Manne & Wene, 1992), however the more common approach in recent times has been to causally link two (or more) separately coherent models in a modular form with bridging between models achieved via the optimization of some (often economic) objective function (Messner & Strubegger, 1995).

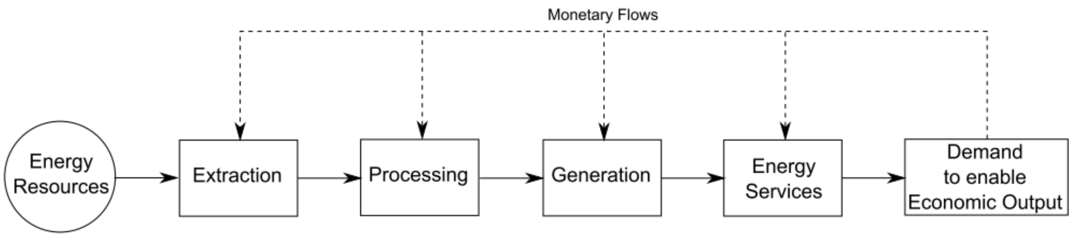


Figure 3-7. Diagram showing the relationship between the main economy and a simplified reference energy system (RES) based on (Seebregts, Goldstein, & Smekens, 2001, p. 3).
Solid arrows represent energy or material flows and dashed arrows represent monetary flows.

3.2.1. MESSAGE

The Model for Energy Supply Strategy Alternatives and their General Environmental impact (MESSAGE) was developed by the International Institute for Applied Systems Analysis (IIASA) as a tool for medium to long term (20 to 100 years, although at the discretion of the user) energy system planning for the purposes of energy policy analysis and scenario development (Messner & Strubegger, 1995). The MESSAGE model interacts with other model components (most notably with the macroeconomic component MACRO) to form a data rich, broad picture view of the effects of various scenarios defined by the user (see Figure 3-8). The scope of the geographical coverage of the MESSAGE model can be defined by the user, although if a global analysis is desired, this is achieved via the agglomeration of several technologically detailed regions with trading between regions.

The core of the MESSAGE model is the definition of a Reference Energy System (RES) wherein demand for (end-use) energy services is supplied by various energy resources via linking through appropriate technologies, each with an associated cost to be determined by the user (see Figure 3-9). The demand for energy services is supplied by the MACRO model component, which incorporates population and increasing living standards to project energy demands over the time horizon of the analysis (Messner & Schrattenholzer, 2000). The two components are linked via minimisation of an (economic) objective function which calculates the cost associated with supplying the demand via a number of energy links. The RES evolves over time due to changing demand from the MACRO system and may be optimised according to other parameters, such as emission profiles.

The system assumes perfect knowledge of the optimal state of the system over all time (as costs are determined at the start of each model run), hence the model does not accurately portray uncertainty within the decision-making process, an issue which some authors have tried to address with models that incorporate fuzzy optimisation procedures (Martinsen & Krey, 2008) or non-linear progressions within technology (Ma, Grubler, Nakicenovic, & Arthur, 2008).

The MESSAGE model has been used to study the implications of a variety of energy scenarios, including a European nuclear moratorium (Messner & Strubegger, 1986), an investigation by the World Energy Council into the IPCC Special Report on Emissions Scenarios (SRES) (Nakicenovic & Riahi, 2002) as well as other Green House Gas (GHG) emissions scenarios (Rao et al., 2008).

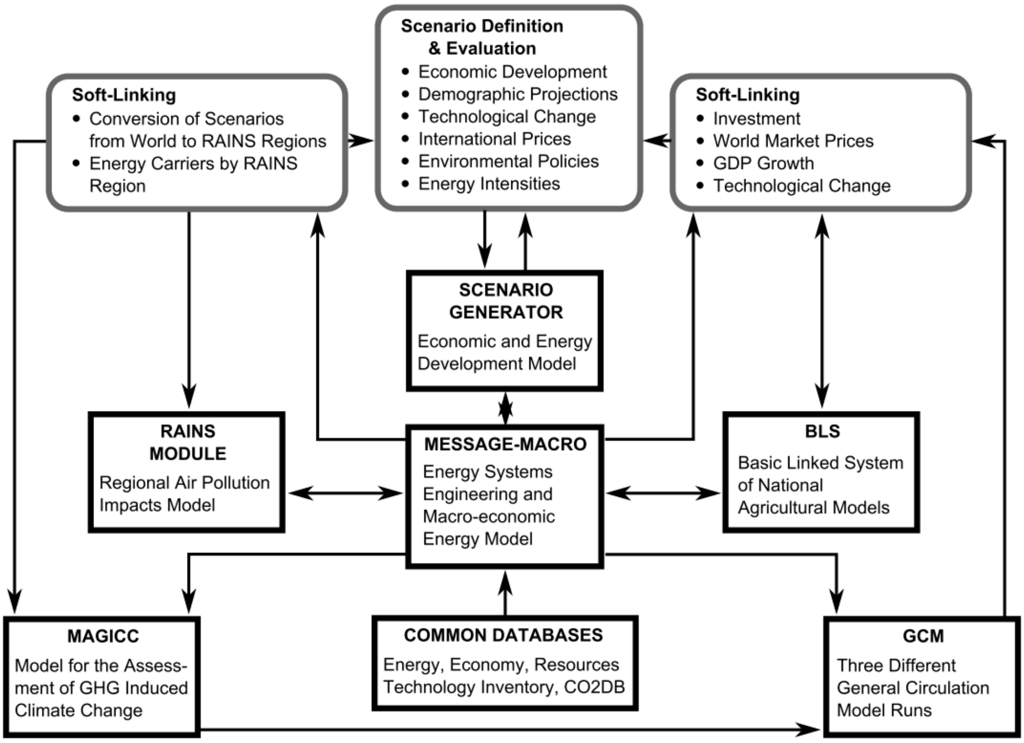


Figure 3-8. The MESSAGE-MACRO model in context from (Messner & Schrattenholzer, 2000).
MESSAGE-MACRO interacts with various other modules to deliver a data rich, broad picture view of the effects of various scenarios defined by the user.

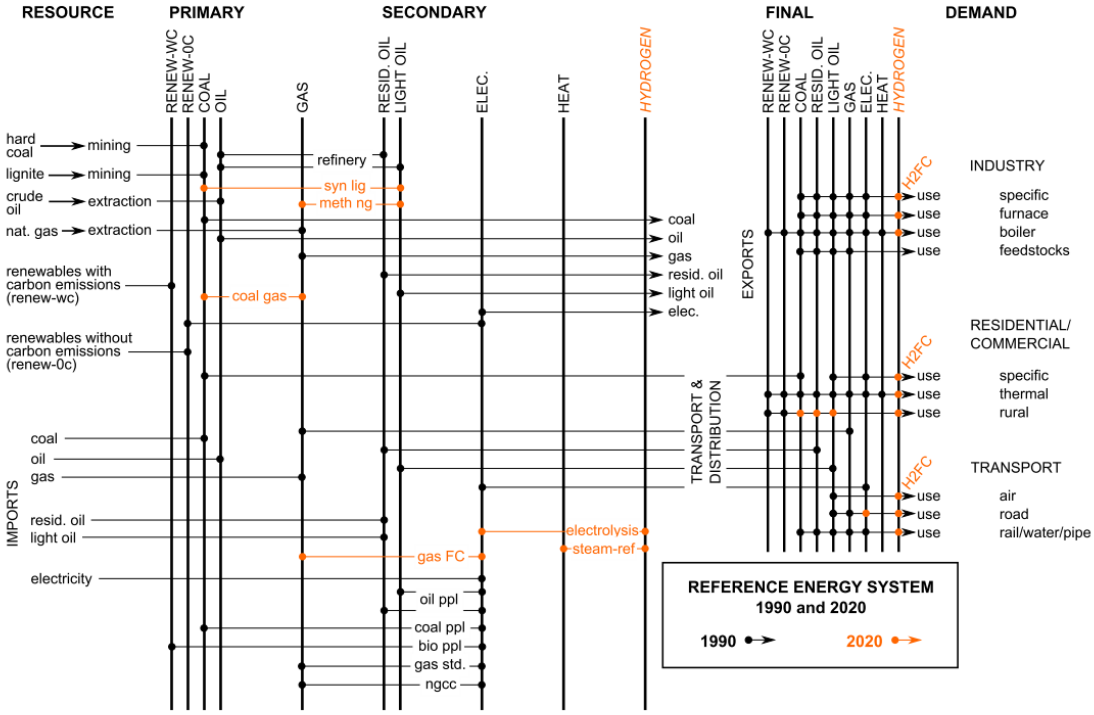


Figure 3-9. The Reference Energy System (RES) that form the basis of the MESSAGE energy model from (Rao, et al., 2008).
Demand for (end-use) energy services is supplied by various energy resources via linking through appropriate technologies, each with an associated cost to be determined by the user. The RES evolves over time due to changing demand from the MACRO system and may be optimised according to other parameters, such as emission profiles.

3.2.2. ERIS

Again developed by IIASA, the Energy Research and Investment Strategies (ERIS) model was produced under sponsorship from the European Commission with the intention of creating a model wherein technological learning (and hence the reduction of costs over time and/or cumulative production) via clusters of associated technologies was endogenous to the model (Turton & Barreto, 2004). The model is a ‘bottom up’ representation of the world disaggregated into 11 regions (Turton & Barreto, 2006). As with MESSAGE, the ERIS model sits in a larger system of model components with which it interacts dynamically.

Again, as with the MESSAGE, the ERIS model displays perfect foresight over the timescale of the analysis and hence knows whether large, long-term investment in new technologies (such as fusion) are likely to someday bear fruit. Obviously this is not the case with real-life decision-making.

3.2.3. IEA WEM model

The International Energy Agency (IEA) have used the World Energy Model (WEM) to produce scenarios for their annual World Energy Outlook (WEO) since 1993 (OECD/IEA, 2009). This model is now used in conjunction with an ECOnomic general equilibrium model, IMACLIM-R, (forming WEM-ECO) to predict trends in patterns of global energy demand and consumption. WEM is disaggregated into 24 geographical regions and is comprised of nearly 16, 000 equations. The model analyses:

- global energy prospects, including trends in demand;
- supply availability and constraints;
- environmental impacts of energy use;
- effects of policy actions and technological change and;
- investment in the energy sector.

Within the model, energy demand is a function of: activity variables (such as GDP or GDP per capita); end-user prices and other variables such as technological change, saturation effects and “other important drivers” (OECD/IEA, 2009).

Demand is disaggregated between four sectors (industrial, residential, services and transport) and is further disaggregated within each of these sectors (e.g. space heating, water heating, cooking and lighting within the residential sector).

The interaction of the bottom-up WEM module with the top-down IMACLIM-R enables the development of various economically and technologically consistent energy supply scenarios. This is achieved by using a dual representation in both financial and physical terms.

Data from the IEA WEO 2008 Reference Scenario for global primary energy demand is shown in Table 3-3 and displayed graphically in Figure 3-11 and Figure 3-12.

Table 3-3. IEA WEO 2008 Reference scenario for global primary energy demand, in EJ/yr (IEA, 2008c). Demand for all energy sources is expected to increase until 2030 with fossil fuels and nuclear still making up 85% of market.

Energy Source	1980	2000	2006	2015	2030	Average growth 2006-2030
Coal	75	96	128	168	205	2.0 %
Oil	130	153	169	189	214	1.0 %
Gas	52	87	101	122	154	1.8 %
Nuclear	8	28	30	34	38	0.9 %
Hydro	6	9	11	13	17	1.9 %
Biomass & Waste	31	44	50	58	70	1.4 %
Other Renewables	1	2	3	7	15	7.2 %
Total	**302**	**420**	**491**	**591**	**712**	**1.60%**

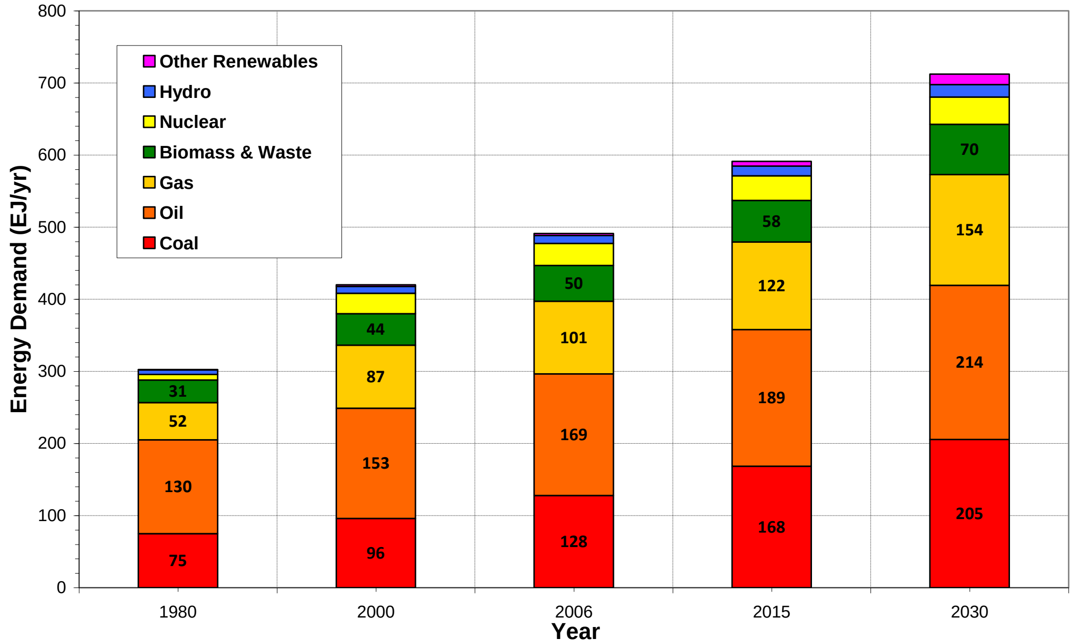


Figure 3-10. IEA reference scenario for global primary energy supply (IEA, 2008c)

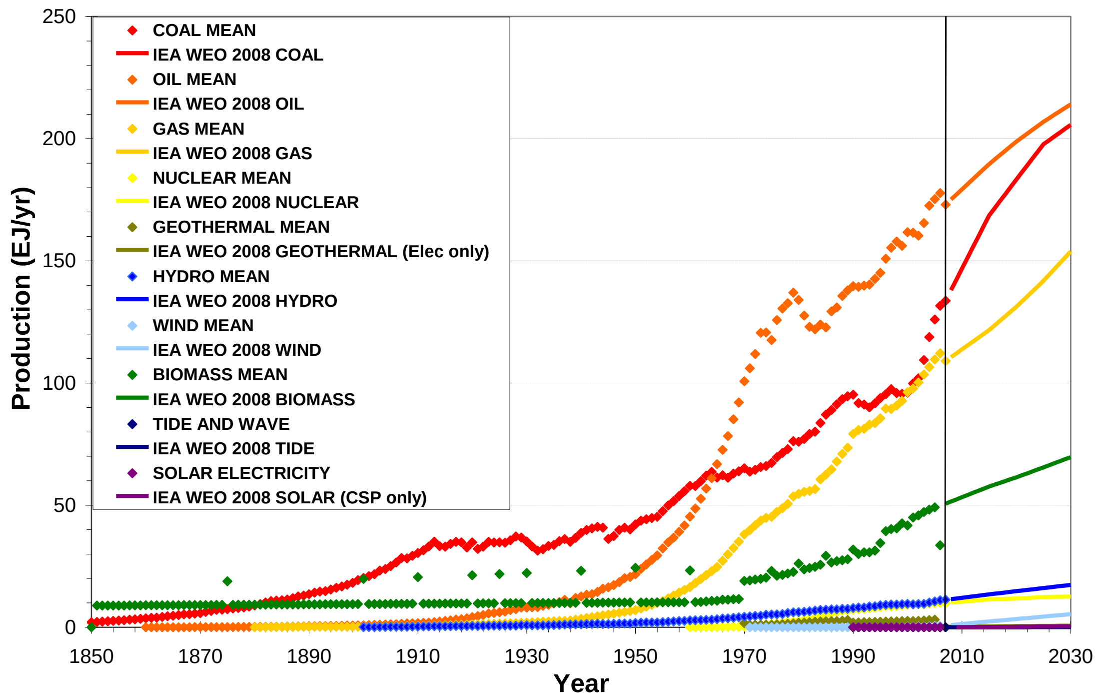


Figure 3-11 Historical production data (dots) plus linear interpolation of projections from IEA WEO 2008 Reference Scenario (solid lines) using WEM model

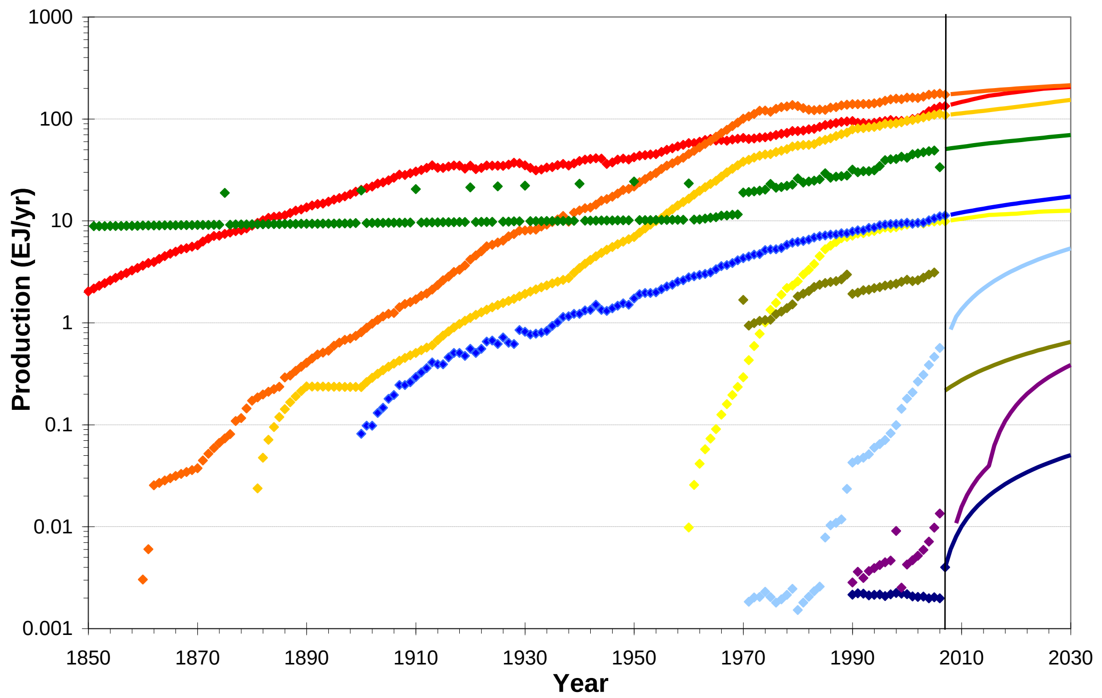


Figure 3-12 Historical production data (dots) plus linear interpolation of projections from IEA WEO 2008 Reference Scenario (solid lines) using WEM model on a logarithmic plot

3.2.4. MARKAL

Originally developed by the IEA, the MARKet Allocation (MARKAL) model is similar in structure to MESSAGE in the use of a Reference Energy System (RES) linking end-use energy demand (disaggregated by sector and function) with primary energy supplies via a variety of possible energy carriers. The optimization routine selects from a variety of potential system configurations using user-defined technology costs to calculate the least cost solution, subject to a variety of constraints, such as environmental or policy issues (Seebregts, et al., 2001).

MARKAL may be linked with a variety of other modules. These include: MACRO, a macro-economic model with endogenously defined energy demand (L. D. Hamilton et al., 1992); MICRO, a micro-economic model with endogenously defined energy demand, responding to price changes (Regemorter & Goldstein, 1998) and; endogenous technology learning (ETL) modelling cost reductions due to cumulative experience (Barreto & Kypreos, 1999).

As with MESSAGE and ERIS, the MARKAL model assumes perfect foresight over the planning horizon, in fact rejection of this assumption in favour of a recursive (step-by-step) decision-making approach means that the model has a "tendency toward "overshoot and collapse"" (Manne & Wene, 1992). Presumably, this is assumed to be an issue of the model structure rather than the market-based allocation mechanism.

3.2.5. Limitations of econometric energy supply models

> "Many energy models cannot be relied upon in forecasting or policy analysis. Indeed, there is little hard evidence to show that such models work. And on a priori grounds, skepticism seems justified. The quality of data inputs is often poor or uncertain, and the internal logic of the models may be open to serious question."(Freedman, Rothenberg, & Sutch, 1983, p. 24)

Below is a list of assumptions identified during analysis of the economic energy models WEM, MESSAGE and MARKAL:

1. that financial costs of energy technologies may be forecast over a time period of decades;
2. that costs of so-called 'backstop' technologies (W. D. Nordhaus, 1973) are independent of market price;
3. that increases in the market price of energy increase the economically available resources, such that "market forces will always (and promptly!) generate enough supply to meet demand" (Abt, 2002);
4. that energy demand is independent of energy supply;
5. that energy demand is a function of population and *per capita* demand for energy services or a function of GDP;
6. that economic growth will continue (this is assumed either explicitly or implicitly through the use of a discounted value on future investments)
7. that all available resources may potentially become economically accessible;
8. that GDP (i.e. economic performance) is independent of energy supply;
9. that economic data represent an "optimal response to the current price vector" (IEA, 2007a, p. 9)

There are a number of problems with the economic energy models of the type discussed above, problems stemming, not so much from the structure of the models but rather from the economic assumptions underpinning them. These problems can be divided into three main categories:

- problems with energy demand forecasting;
- problems with price-based allocation methods and;
- issues of sustainable scale.

Each of these issues is briefly outlined in turn. Before exploring these issues more deeply, however, it is worth understanding how neoclassical economic theory understands the production of non-renewable resources.

In his seminal paper, *The Economics of Exhaustible Resources*, Harold Hotelling (1931) analyses resource production as determined by the tension between the producer wanting to extract the resource as quickly as possible (and thus avoid diminishing value of the resource due to the social discount rate) and the consumer demand curve, which negatively correlates the value of the produced resource to the amount that enters the market, such that,

> "If a mine-owner produces too rapidly, he will depress the price, perhaps to zero. If he produces too slowly, his profits, though larger, may be postponed farther into the future than the rate of interest warrants." (Hotelling, 1931, p. 139)

One of the primary assumptions within the analysis is that the resource allocator is aware of the total stock of the resource, any technological development that may affect the resource production and the level of demand over all time, i.e. how scare is the resource. Norgaard (1990) appeals to the use of these assumptions to critique 'measuring resource scarcity' by tracking the long-run price of such resources. He simplifies the Hotelling-type model as a simple syllogism:

Major Premise:	If resources are scarce, and
Minor Premise:	If resource allocators are informed of resource scarcity,
Conclusion:	Then economic indicators will reflect this scarcity.

Studies of long-run price of resources, such as Scarcity and Growth by Barnett and Morse (1963) attempt to "run this argument backwards" (Norgaard, 1990, p. 22), using the decreasing price of resources over time as evidence against the assumption that resources are scarce. Such evidence may, however, simply refute the assumption of informed allocators.

Since economic scarcity is defined relative to demand in each moment of time, intra-temporal abundance may belie inter-temporal scarcity in the future (D. B. Reynolds, 1999). As Slesser et al. point out,

> "The oil will not run out abruptly, of course. Price signals will prevent that. What is far from certain is whether the price signals will reach the market in time to develop the alternative energy systems in sufficient volume. " (Malcolm Slesser, et al., 1997, p. 107)

Problems with demand forecasting

Since economic forecasts are often made by projecting historic trends into the future, they have been likened to driving a car blindfolded, following directions given by a person who is looking out of the back window (Abt, 2002; Bishop & Bishop, 2004). Demand functions generated using macro-economic assumptions regarding future (expected) economic growth are particularly vulnerable to this criticism, since any relationship between energy consumption and GDP is necessarily empirical. Demand functions generated using micro-economic assumptions regarding *per capita* demand for energy services (heating, lighting, transport, etc.) are less weak; however the use of *per capita* demand conceals vast disparities in energy use distribution, especially at a regional or global level.

Such forecasting must also make a large number of assumptions, any one of which may be invalid, or inappropriate. One example is the assumption of the "energy ladder" which postulates that household energy use progresses from 'traditional' biomass fuels (wood, dung or stover) through solid or liquid fossil fuels (coal or kerosene) to 'modern', clean-burning forms (LPG, natural gas or electricity) as household income increases (Barnes & Floor, 1996). Many authors have questioned the validity of this assumption (Martins, 2005; Masera Barbara & Omar, 2000; van Ruijven et al., 2008). Other assumptions include the correlation between energy demand and income levels or GDP. Elasticity in demand in the face of price changes are assumed using a Cobb-Douglas production function of labour, capital, resources and energy (Zhang & Folmer, 1998). Issues concerning the conflict of such production functions with thermodynamic laws were discussed in Section 0.

Problems with price-based analysis

> "[Economics is] the science that treats phenomena from the standpoint of price" (Davenport, 1919, p. 25)

> "the problem is not one of availability of energy resources, but of how the world moves from dependence on cheap, convenient, but exhaustible sources of energy, such as crude oil and natural gas, to reliance on more abundant, but less convenient and hence more expensive sources of energy, such as coal, nuclear power and solar power." (Ulph, 1980, p. 54)

Economics uses price in the attempt to find a common measure for the many economic goods and services that may be exchanged, particularly within modern consumer societies(Lietaer, 2001). The use of a price based analysis within economic models has three main limitations: firstly, the problem of 'price forecasting' over long periods of time; secondly, that production costs are not influenced by energy prices and; thirdly, that not all important features may be captured by price.

Price is used as the signal by which so-called "backstop" technologies (W. D. Nordhaus, 1973) begin production, when the market price rises above their production cost. However, these production costs represent forecasts of estimated costs of production over the time horizon of the model. Given the "inability of oil analysts and macroeconomists to forecast demand, supply, and price of oil over the last twenty-five years" (Abt, 2002, p. 87) it seems unlikely that projections of costs will fare any better. Such forecasts rely on constant price-elasticity of factors of production, however, as Freedman et al. (1983) point out,

> "As the cost-share of energy goes up, its price elasticity should change… The technical assumption of constant elasticity is exerting an influence on the forecasts, and this influence gets stronger as the scenarios diverge from the circumstances that obtained during the fitting period." (Freedman, et al., 1983, p. 29)

Within the economic models there is an assumption that production costs of backstop technologies are independent of energy market prices. Reynolds (1998) questions the validity of this assumption by analysing the cost of unconventional sources of oil to changes in the market price of oil. Figure 3-13 shows the relationship between the 'rack price' (the price at point of retail) of ethanol and that of unleaded gasoline in Nebraska between 1983 and 2010. There is a strong correlation ($R^2 = 0.7621$) between the two prices, indicating that the price of alternative fuels (i.e. the 'backstop' technology) is dependent on the market price of energy sources.

Ulph (1980), in his survey and critique of energy models, makes a case for the development of energy models to guide policy, stating,

> There are many reasons… why real markets deviate from the competitive ideal, but perhaps the most important, for present purposes, is the absence of a full set of future and risk markets. This means that future price signals are not available to guide depletion policy or development of alternative energy sources. An obvious role for energy forecasting studies, therefore, would appear to be to act as a surrogate for future markets by providing forecasts of future prices. To produce such forecasts, one would need a world model (since energy resources can be traded), with a dynamic specification of demand that took account of interfuel substitution and conservation, assumptions about the likely reserves of exhaustible energy resources, and costs of production for existing and alternative energy sources. A crucial requirement is a model of intertemporal resource allocation, showing how owners of exhaustible energy sources choose to deplete their resources,

since the important question concerns the timing of the increase in energy prices. (Ulph, 1980, p. 55)

However, if the production cost of 'backstop' technologies truly are dependent on market prices for energy resources then the argument he puts forward is circular. Future energy prices are implicitly assumed in the forecasted costs of production therefore cannot be used to predict future energy prices.

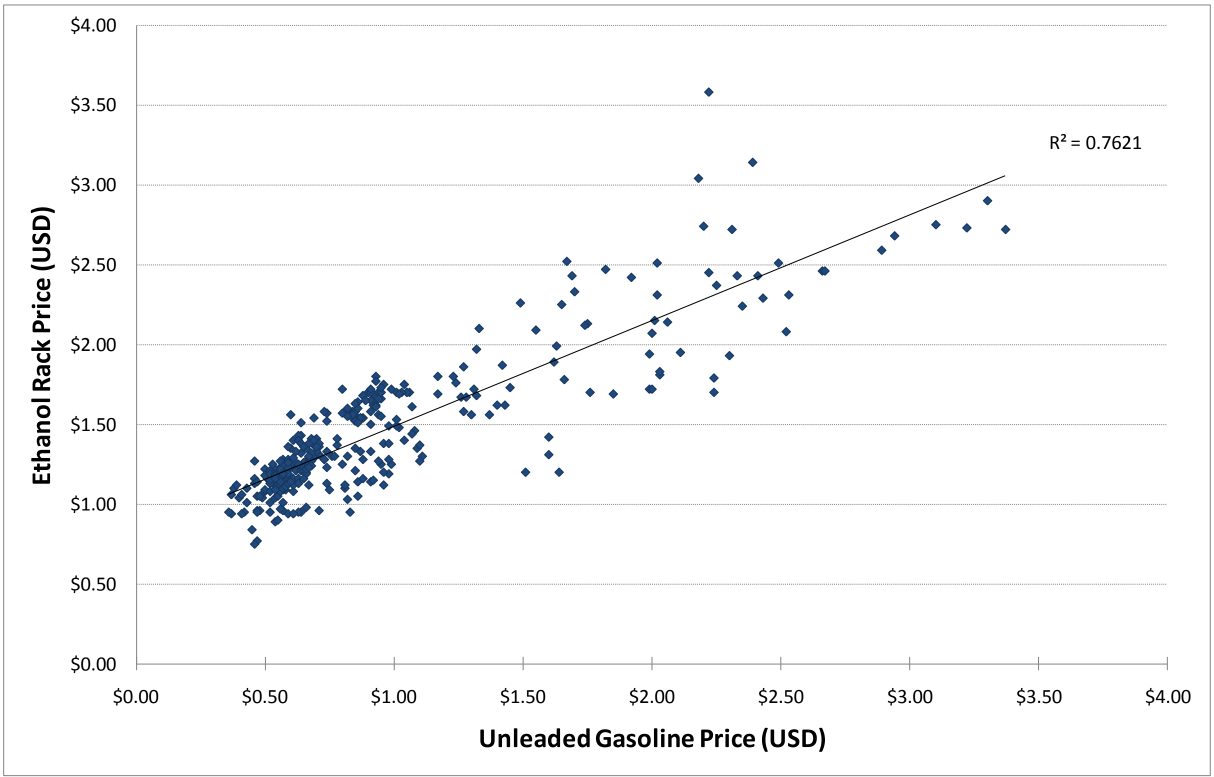


Figure 3-13 'Rack price' of ethanol plotted as a function of the 'rack price' of unleaded gasoline between 1983 and 2010, with data from (NEO, 2010).
There is a strong correlation between the prices of the two over the period.

The third issue with price-based analyses concerns interactions between humans and nature. Money may be used as a metric only for interactions between people. Within economic models, resources taken from nature are either assumed to be free or are valued according to their 'opportunity cost', i.e. the value of whatever someone is willing to forego in order to obtain them (Goodstein, 2008, p. 164). However, the 'opportunity cost' of, for example, unconsumed oil reserves left in the ground will often be dictated by the presumed value of that resource for use at some point in the future, dependent on a variety of assumptions relating rates of interest as well as other technological and social factors (Rees, 1985).

Robert Ayres here argues that non-monetary measures are necessary in order to inform policy regarding human-nature interactions, saying,

> "Yet, many environmental features can be quantified in terms of other, non-monetary measures. In the absence of reliable monetary measures (i.e. prices) such quantification is all the more necessary for making rational policy decisions… since man-nature interactions are not pure monetary transactions governed by market mechanisms, in general, they cannot be understood in terms of a pure market model of the world. Other elements must be added also… The new elements that must be added to the economic models are material stocks and flows, and physical (i.e. thermodynamic) and biological relationships"(Ayres, 1998, pp. 2-5)

The point is re-iterated by Slesser et al. (1997),

> "environmental issues are far too complex to be handled by simple monetary cost benefit analysis alone. The inevitable interaction between waste production, pollution abatement, capital investment, energy requirement and environmental space needs a holistic approach: one which works back from Nature to human activity." (Malcolm Slesser, et al., 1997, p. 187)

These issues suggest that adding to the price-based analysis of standard econometric models, by including energy and material flows, may enable a more holistic view, more in keeping with the aims of sustainable development

Issues of sustainable scale

The final limitation of economic energy models concerns their inability to explicitly determine an optimally scale for the energy sector (and hence the economy as a whole) which many authors feel is of paramount in consideration of sustainable development (D. Cook, 2005; Costanza, 1994; Daly, 1977; Malcolm Slesser, et al., 1997; UK Govt., 2005). Within economic models, energy demand is a function of income (at either the level of the individual or the national economy) and will be dependent also on the market price of energy. Proponents of such models argue that by 'internalising' environmental costs, such as pollution abatement, within the production costs within the model allows issues of sustainability to be addressed (W. D. Nordhaus, 1992; D. Wilson & Swisher, 1993; Zhang & Folmer, 1998). However, as discussed in Section 0, measuring such 'costs' relies on a huge number of assumptions regarding social (what society thinks has value), economic (how it is valued) and technological development.

3.3. Physical resource accounting models

The need for physical resource-based analysis of economic activities has been discussed by many authors (Ayres, 1998; Gever, et al., 1991; Schenk & Moll, 2007; Schipper, Unander, Murtishaw, & Ting, 2001; Malcolm Slesser, et al., 1997; Worrell, Price, Martin, Farla, & Schaeffer, 1997). The view may be summed up by two quotes:

> "Conventional economic models fall into these traps [thinking that rising prices will 'create' new energy supplies] because they operate under one basic assumption: that the production of fuels and other resources is determined solely by conditions within the economy… We believe that the reverse is now true: that physical changes in the resource base limit U.S. fuel production, which in turn influences economic conditions, and that this effect will become inexorably stronger as world oil production becomes similarly constrained. This assumption is antithetical to the philosophy behind 'internal' economic models, and hence cannot be built into them *post hoc*." (Gever, et al., 1991, p. 114)

> "It [money] is purely and simply a device for dealing with human-to-human interactions. And for that reason alone money has one important failing. It cannot deal with human-to-Nature interactions." (Malcolm Slesser, et al., 1997, p. 22)

Abt (2002) questions the accuracy of long-range energy price forecasting, the cornerstone of the economic energy modelling approach, stating,

> "It seems important to know whether the inability of oil analysts and macroeconomists to forecast demand, supply, and price of oil over the last twenty-five years is a problem intrinsic to only oil, or to the forecasting of all energy prices, or economic forecasting, or indeed all long-range (ten-to-twenty-year) forecasting itself. We want to know if we can, through analytical methods, incorporating contributions of other disciplines than economics, correct errors in forecasting energy demand, supply and prices for different forms of energy, five to twenty years out.
> If we cannot forecast prices of one kind of energy supply any better than another, then we have no rational basis for the long-range planning of the best mix of long lead-time investments in energy-producing power plants and energy-intensive industries and products." (p. 87)

In an attempt to create energy-economy scenarios that are guaranteed to be consistent with the laws of thermodynamics, some authors have proposed using energy analytic methods favoured by ecologists (Daly, 1999; Georgescu-Roegen, 1975; Charles A.S. Hall, et al., 1986; Odum, 1996).

Problems of using price costs within energy-economic models, as discussed earlier, arise due to the different laws that govern the creation of money, artificial constructions of the financial system, as opposed to those laws governing physical processes, such as the laws of thermodynamics. In theory, the financial costs associated with the manufacture of a material, a tonne of steel may decrease forever, however, there are strict fundamental limits to the amount of energy that must be expended to mine and process the ore required to produce a tonne of steel.

The use of embodied energy as a numeraire immediately sets physical limits on economic processes consistent with the mass and energy balances requirements of the first law of thermodynamics. The inclusion of decreasing marginal returns on energy production allows the model to adhere to the second law of thermodynamics. Energy costs associated with energy transformation activities are also less subject to change in the face of changing prices of inputs. Many of the problems of using prices are thus obviated by using physical units of measurement.

The energy-economy system is represented using energy circuit language in Figure 3-14. The main distinction between this representation and that of the econometric models is that not only money, but also energy (mainly embodied in the form of physical capital) must flow back from the main economy to the energy sector. This introduces the concept of net energy yield and an energy-return-on-investment (EROI) ratio.

A number of models based on the biophysical systems approach have been constructed since the seventies. The most well-known of such models is the (in)famous World3 model that formed the basis of the "Limits to Growth" report (D. H. Meadows, et al., 1972). Often the model is developed with a particular question in mind. The question 'what is the instantaneous upper limit to global economic activity?' inspired the development of the System, Time, Energy and Resources (STER) global energy supply model (Hounam, 1979). Consideration of physical components of the energy-economy system allows exploration of the dynamic interaction of the system elements. Such interest lay behind the models developed by Baines, Peet and Bodger (Baines & Peet, 1983; P.S. Bodger & Baines, 1988).

In the early nineties came the development of the Energy and Capital Creation Options[15] (ECCO) model (M. Slesser, 1992). The ECCO methodology has been applied on a global scale (J. King & Slesser, 1995) as well as to a number of national economies (Malcolm Slesser, et al., 1997) including European countries (Battjes, 1999), New Zealand (Ryan, 1995) and Australia (Foran & Crane, 1998).

[15] Later this became 'Evolution of Capital Creation Options'.

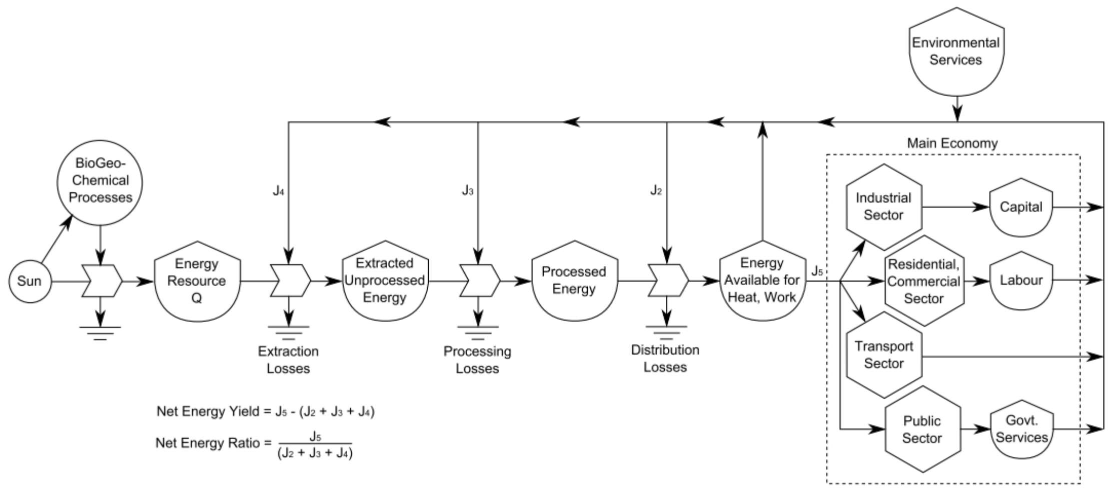


Figure 3-14. Diagram to show the relationship between the main economy and the energy sector from (Charles A.S. Hall, et al., 1986, p. 38).
All arrows represent energy flows (all material flows being 'embodied' as energy). The energy transformation sector passes energy to the main economy and relies on material and energy flows from the main economy.

3.3.1. World3

The World3 model was built on the principles of dynamic systems modelling (Forrester, 1971, 1972; B. M. Hannon & Ruth, 2000) to investigate the interaction of five major trends of global concern: increasing industrialisation, rapid population growth, pervasive malnutrition, depletion of non-renewable resources and environmental degradation (D. H. Meadows, et al., 1972).

A variety of scenarios were run using the model which showed “a strong tendency to overshoot and collapse” (D. H. Meadows, et al., 1992, p. 139). This tendency is due to a number of interacting factors built into the model:

- that growth of both population and the economy is exponential;
- there are physical limits to the sources of materials and energy;
- there are limits to sinks that absorb waste;
- signals regarding physical limits are distorted and delayed;
- response to signals is also delayed and;
- system limits are erodible when overstressed or overused.

The contention of the authors is that each of these properties of the model is fairly representative of the system being modelled.

3.3.2. Bodger and Baines dynamic model

Bodger and Baines (1988; 1989) developed and generalised a model first expounded by Baines and Peet (1983) for New Zealand. Much like the World3 model, Bodger and Baines utilised system dynamics principles. One of the main aims of the model was to understand the underlying physical interaction of the global energy-economy system resulting in the Marchetti curves (see Section 3.1.2).

Within the model, EROI (called *accessibility*) was used to switch demand between existing and incoming energy sources, but was assumed constant over the entire production cycle. Incoming energy sources were assumed to have higher EROI than existing energy sources. The values for energy yields were never compared with historic energy production data.

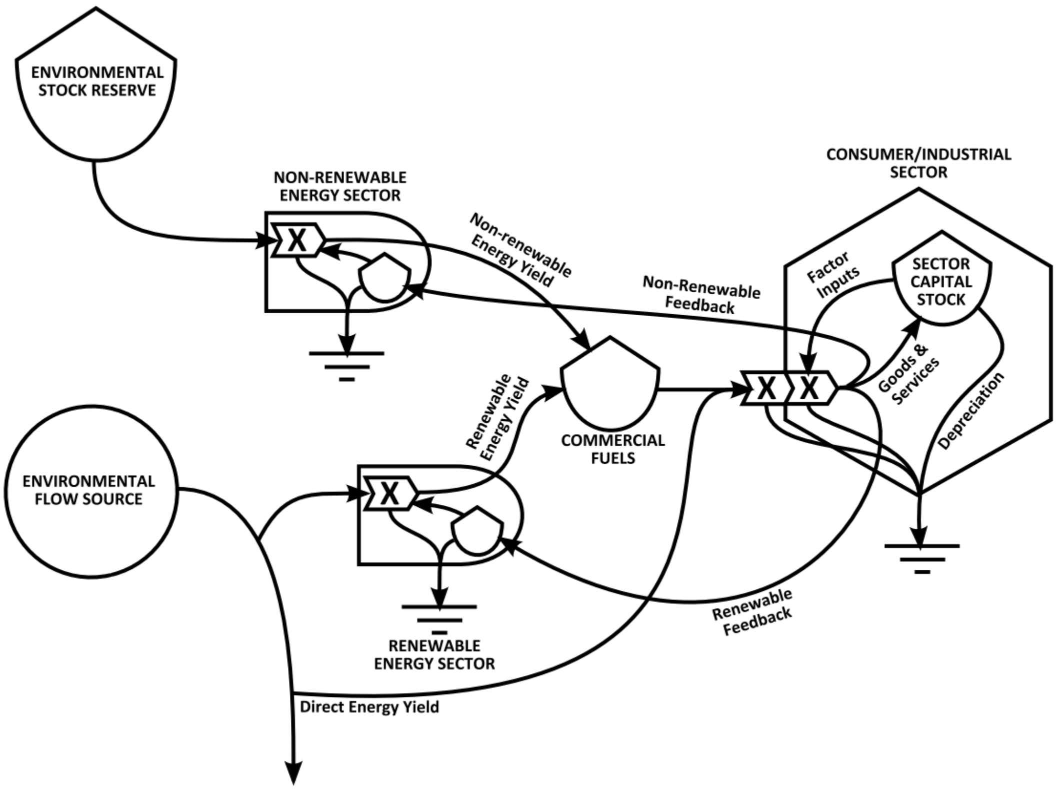


Figure 3-15. Energy circuit diagram for energy-economy dynamic interaction from (P.S. Bodger & Baines, 1988)

3.3.3. ECCO

Developed by Malcolm Slesser (1992), the Evaluation of Capital Creation Options (ECCO) explores issues of physical resource limitations on the economic opportunities available to society. The basic metric for the model is energy; either in the form of energy flows, or energy embodied in the form of natural capital, such as oil or coal, or in the form of infrastructure (man-made capital stock). For a more thorough treatment of the ECCO method and application to specific economies see Ryan (1995) and Battyes (1999).

Within the ECCO model are defined three types of natural capital:

- depletable – non-renewable energy resources, such as coal
- recyclable – mineral resources not consumed by their use, such as iron
- renewable (or potentially renewable) – resources which are naturally replenished over timescales commensurate with their consumption, such as biomass or fish stock.[16]

The core of the ECCO methodology is a basic global model – CORECCO (see Figure 3-16). The model is composed of four sectors: population, agriculture, energy production and industrial. The dynamic interaction of these sectors is modelled through the depletion of energy stocks and subsequent increasing capital requirements for energy extraction.

Within the ECCO model, EROI was included with the variable MARGINAL CAPITAL REQUIREMENT FOR ENERGY. The value of the variable did change through the production cycle, however the function used is fixed and is never explicitly explained nor linked to energy analysis data. The output from the model is nowhere compared with historic production data.

[16] Such resources are 'potentially renewable' since they may be depleted if harvested at a rate greater than their replenishment.

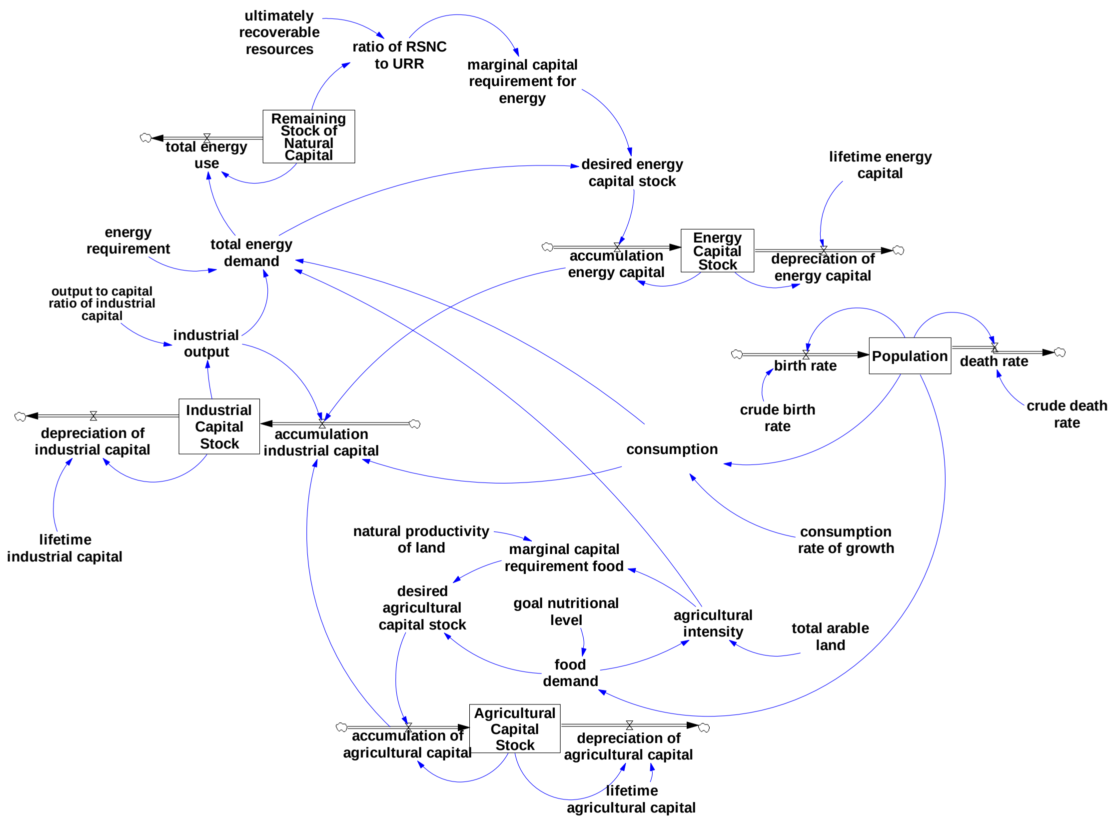


Figure 3-16. Structure of CORECCO model from (M. Slesser, 1992)

3.4. Summary

The three types of energy models that have been looked at represent two different classes of models. The first group of models based on fitting growth curves to historic data, represent a view of the energy-economy system as an open-loop system which, as such, may be modelled analytically for the purpose of defensive prediction, since the antecedent conditions driving the system are assumed to be factors *exogenous* to the model, i.e. they are outside the sphere of influence of the model user. The issue with using such simplistic models to describe the energy-economy system is well expressed in this quote from Costanza et al,

> “the environment, society, and the economy each represent complex systems characterised by nonlinearities, autocatalysis, time-delayed feedback loops, emergent phenomena, and chaotic behavior. Furthermore, these fundamental systems are linked in ways that we are only just beginning to appreciate.” (Costanza, Leemans, Boumans, & Gaddis, 2007, p. 419)

The econometric and physical resource accounting models instead perceive the energy-economy system as a complex, self-regulating, closed-loop control system subject to non-linear dynamics. As such these models do not attempt to find an analytic solution, but instead rely on numerical simulation. The purpose of the predictions made may either be defensive or pro-active, depending on the scenario developed by the user.

A major problem with econometric models is the assumption that all of the important dynamics of the energy-economy system can be captured using money as a lens. Price holds an important position within the models discussed above. It plays two essential roles: one, as a measure by which the system as a whole can be optimised to calculate a 'least cost' solution and; two, as a metric of comparison between various energy technologies such that substitution may occur. In this sense these models borrow heavily from the neo-classical economic theories on which they are based.

Price costs of technologies included within the model are determined by the user and (as discussed earlier) are assumed to be known over all future times within the model. Given the sometimes decades-long timescales of the models, this is an exceptionally strong burden to place on the price mechanism considering the extreme volatility of energy prices, especially oil, in the face of supply scarcity (He, Cheng, & Wang, 2009). The situation is well expressed by this quote from the IEA,

> "the sources of oil to meet rising demand, the cost of producing it and the prices that consumers will need to pay for it are *EXTREMELY UNCERTAIN*, perhaps more than ever" (IEA, 2008c, emphasis added).

Dramatic changes in the price of oil also have had knock-on effects on the price estimates of alternative energy sources, such as shale oil, by as much as a six-fold factor (D. Reynolds, 1998). The lack of a physical basis for substitution between energy sources within the models means that they are extremely sensitive to changes in price inputs. Prices are also assumed for, as yet, undeveloped technology options, such as Carbon Capture and Storage (CCS). These technologies must be at least as susceptible (if not more so!) to changes in cost estimates as alternative energy sources. Least-cost optimisation based on such assumptions is tantamount to pre-determining the future energy mix.

Other researchers who have investigated the transition of the energy system from fossil fuels to running predominantly on renewable sources include David MacKay (2008), Ted Trainer (Trainer, 2007) and the World Energy Assessment ((WEA, 2000).

MacKay considers the ability of supplying current demand for energy services by renewable energy sources. In his 'plan' demand is divided between electricity (18%), heating (41%) and transport (41%). His analysis looks at the whether the technical potentials of renewable sources are great enough to supply this demand. His conclusion is that, “the non-solar renewable may be ‘huge’, but they are not huge enough. To complete a plan that adds up, we must rely on one or more forms of solar power. Or use nuclear power. Or both.” (p. 239). MacKay’s analysis does not incorporate changing energy consumption in the future nor the energy required to produce the renewable infrastructure, hence represents what could be termed as a ‘static snap-shot’.

Trainer provides a semi-numerical analysis of the potential of renewable energy sources but also analyses infrastructure necessary to cope with the variability and intermittency of renewable sources, such as energy storage. He concludes that renewable energy sources cannot sustain our current energy demands.

The WEA provide a long-term (1990 – 2100) analysis of the global energy system. One of the scenarios under consideration is a push towards a greater proportion of energy from renewable resources (reference scenario C1), wherein renewable energy sources supply 80-85% of the total 880 EJ in the year 2100. Despite using a dynamic model that incorporates the development from our current energy mix to the mix represented in the scenario, the only criterion for assessing whether renewable energy sources can supply the demand is that the demand is less than the technical potential. The issues of EROI nor physical capital resources are not considered.

There is a need for a dynamic model of the global energy-economy system that incorporates both the evolution of the EROI and physical capital requirements of the energy system during the transition to renewable energy sources. This model should make explicit use of energy analysis and historic production data for the purposes of calibration.

CHAPTER 4. A DYNAMIC FUNCTION FOR EROI

In this chapter, a dynamic function for the EROI of an energy source over the production cycle is presented and discussed. Within the GEMBA model, EROI plays a vital role by mediating between total energy demand and the energy demand to be provided by each energy source, via the allocation function; as well as between the energy demand and the required energy sector capital stock and between energy sector capital stock and annual energy production.

4.1. Theoretical considerations

Most estimates of EROI are made as static estimates of a resource at a particular moment in time, however some 'dynamic' estimates have been made which track the EROI of a particular resource as it changes over time (see Section 6.1).

One such study has been conducted by Costanza and Cleveland (1983) of oil and gas production in Louisiana. They identify a very characteristic shape for the EROI as a function of cumulative production, P, as shown in Figure 4-1. The EROI of the resource initially increases before reaching some point of production, $\boldsymbol{P_{max}}$, at which the energy return is at its maximum value, before declining and eventually dropping below the breakeven limit represented by an EROI value of one.

Assuming that this cycle corresponds with the 'production cycle' identified by Hubbert for non-renewable resources (see Section 3.1.1), at what point in the production will $\boldsymbol{P_{max}}$ occur? It is conjectured that $\boldsymbol{P_{max}}$ should occur a quarter of the way through the production cycle. Hubbert's curve for annual production, $\dot{P}$, as shown in Figure 5, initially increases exponentially before reaching a peak and thereafter declining. This curve passes through a point of inflection a quarter of the way through the cycle, corresponding to a maximum in the rate of change of annual production, i.e. the first derivative of annual production with respect to time, $\ddot{P}$.

The purpose of investment in increasing infrastructure is to buy an increase in annual production, therefore we may say that:

$$\dot{P}\ [EJ] \propto EROI\ \times Investment \qquad [4\text{-}1]$$

Presumably investment in infrastructure increases exponentially (or at the very minimum linearly) between T_0 and $T_{1/2}$. If so, then annual production and capital investment are correlated between T_0 and $T_{1/4}$. Thereafter, each unit of capital investment earns less return in energy production, reflected in the decreasing rate of change of energy production, $\ddot{P}$. Since EROI is the correlating factor between capital investment and energy production, then EROI must be decreasing and, hence, must have peaked before $T_{1/4}$ in the production cycle. This would not be the case if investment were constant (in which case P_{max} would occur when $\ddot{P}$ is a maximum) or, if investment were decreasing over the period. However, both of these cases seem unlikely.

Within this work, it is posited that this curve for the EROI is representative of, not only Louisiana oil and gas, but all energy sources, including renewable energy sources. However, in the case of renewable energy sources the curve is a function of annual, rather than cumulative, production. It is further assumed that this EROI function is a product of two components: one technological, $\boldsymbol{G}$, that serves to increase energy returns as a function of resource production, $\boldsymbol{\rho_k}$ (which may serve as a proxy measure of experience), i.e. technological learning; and the other, $\boldsymbol{H}$, diminishing energy returns due to declining physical resource quality.

$$\mathrm{EROI_k[dmnl]} = \mathrm{\varepsilon_k F(\rho_k)} = \mathrm{\varepsilon_k G(\rho_k) H(\rho_k)} \qquad [4\text{-}2]$$

Where ε is a scaling factor that increases the EROI and ρ is cumulative production normalised to the size of the ultimately recoverable resource (URR)[17], such that:

$$\rho\ [dmnl] = \frac{P}{URR} \qquad [4\text{-}3]$$

[17] Within this work URR is assumed to be the total resource that may be recovered at positive net energy yield.

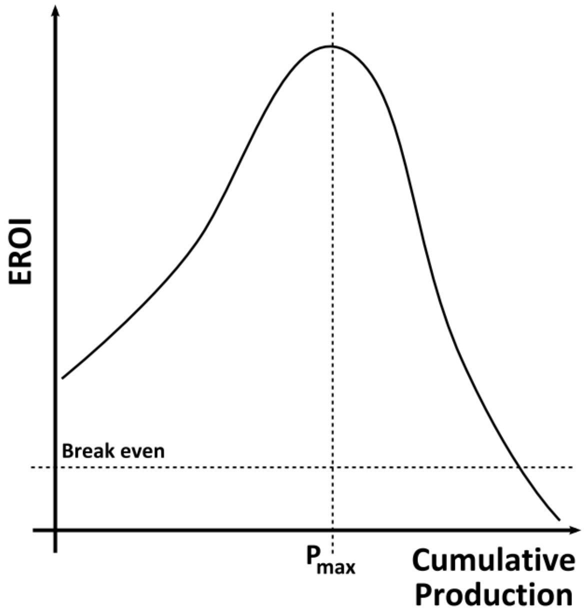


Figure 4-1. EROI as a function of production from (Costanza & Cleveland, 1983).
EROI is assumed to be a product of technological and physical components.

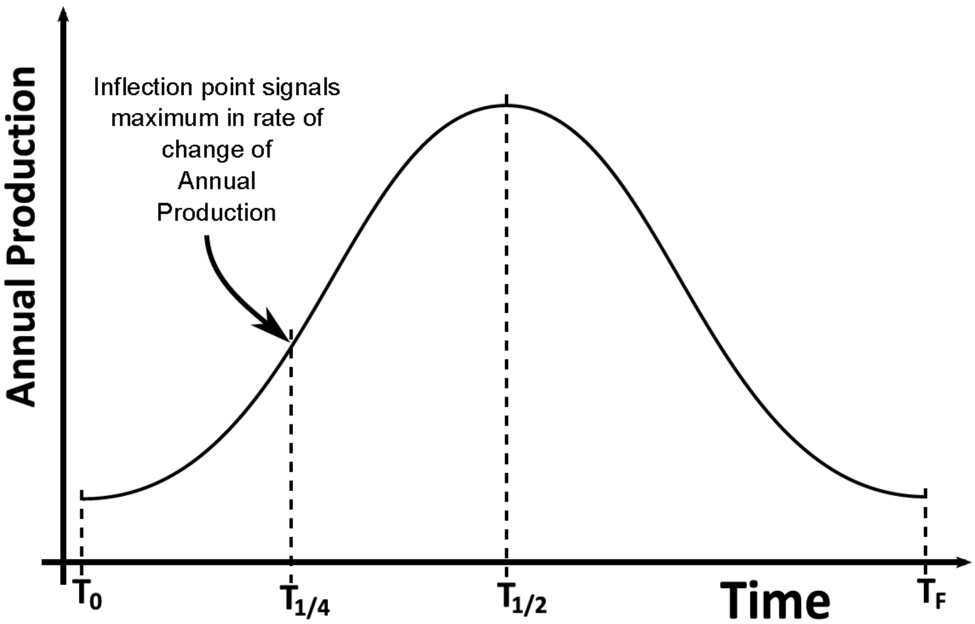


Figure 4-2. Annual production over the entire production cycle of a non-renewable resource: the 'Hubbert Curve'.
If production is symmetric then the maximum change in the annual production occurs at the inflection point at $T_{1/4}$.

4.1.1. Technological learning

It is assumed that the technological component of the eroi function asymptotically increases as a function of production as shown in Figure 4-3There are two factors that will influence this technological component of the EROI function: how much energy must be embodied within the equipment used to extract energy and how well that equipment performs the function of extracting energy from the environment. We assume that both of these factors are subject to strict physical limits. Firstly, that there is some minimum amount of energy that must be embodied in order to function as an energy extraction device, for instance the foundation of a wind turbine must successfully endure a large moment load. Secondly, there is a limit to how efficiently a device can extract energy. We further assume that, as a technology matures, i.e. as experience is gained, the processes involved become better equipped to use fewer resources: PV panels become more efficient and less energy intensive to produce; wind turbines become more efficient and increasing size allows exploitation of economies of scale. These factors serve to increase energy returns. However, it can be expected that these increases are subject to diminishing marginal returns as processes approach fundamental theoretical limits, such as the Lancaster-Betz limit in the case of wind turbines.[18]

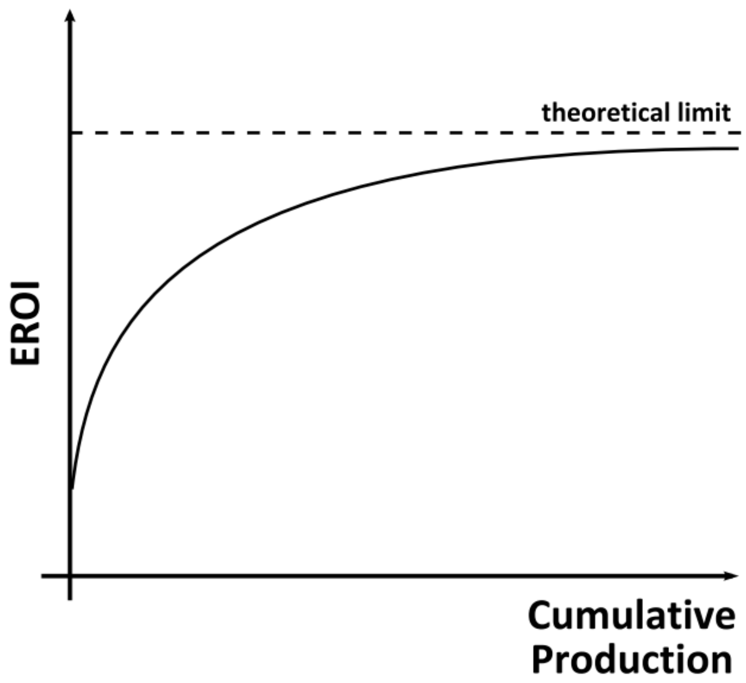


Figure 4-3. Technological component of EROI function.
EROI increases asymptotically to some limit, sometimes represented by a fundamental theoretical limit such as the Betz-Lancaster limit for wind turbines.

Technological learning curves (sometimes called cost or experience curves) track the costs of production as a function of production. These often follow an exponentially declining curve asymptotically approaching some lower limit. The progress ratio specifies the production

[18] This limit states the maximum power (and thus absolute limit to the efficiency) that can be extracted by a horizontal axis wind turbine.

taken for costs to halve. Between 1976 and 1992, the PV module price per watt of peak power, W_p, on the world market was 82% (IEA, 2000). This means that the price halved for an increase in cumulative production of 82%. Lower financial production costs should correlate with lower values of embodied energy (Costanza & Cleveland, 2004; Charles A.S. Hall, et al., 1986; Liu, et al., 2008). The specific form of the function used in the GEMBA model is:

$$G(\rho_k) = 1 - \Xi_k e^{-\xi_k \rho_k} \qquad [4\text{-}4]$$

Where $0 \leq \Xi \leq 1$.

Here $\boldsymbol{\Xi_k}$ represents the initial value of the immature technology and $\boldsymbol{\xi_k}$ represents the rate of technological learning through experience which will be dependent on a number of both social and physical factors. This rate is assumed constant.

4.1.2. Declining resource quality

The physical resource component of the eroi function is assumed to decrease to an asymptotic limit as a function of production, as shown in Figure 4-4. In general, those resources that offer the best returns (whether financial or energetic) are exploited first. Attention then turns to resources offering lower returns as production continues. In general the returns offered by an energy resource will depend upon the type of source, formation and depth of the reserve, hostility of the environment, distance from demand centres and any necessary safety or environmental measures. The costs of production often increase exponentially with increases in these factors (E. F. Cook, 1976). The result is that the physical component of the eroi of the resource declines as a function of production. It is assumed that this decline in eroi, ***H*** will follow an exponential decay:

$$H(\rho_k) = \Phi_k e^{-\phi_k \rho_k} \qquad [4\text{-}5]$$

Where $0 \leq \Phi \leq 1$.

Here $\boldsymbol{\Phi_k}$ represents the initial EROI value of the virgin resource assuming an optimal production technology and $\boldsymbol{\phi_k}$ represents the rate of degradation of the resource due to exploitation. Again this rate is assumed constant.

Use of this exponentially declining curve is justified by considering the distribution of energy resources. Some of these resources will offer large energy returns due to such factors as their energy density (e.g. grades of crude or coal), their ease of accessibility (e.g. depth of oil resources, on-shore vs. offshore), their proximity to demand centres (e.g. Texan vs. Polar oil) and possible other factors. The EROI of one particular source should be, if not normal, then most likely displays a positive skew, i.e. the median is less than the mean, as depicted in Figure Figure 4-5. For example, there are more sites with lower average wind speeds than with higher wind speeds. If we now assume that sites will be exploited as a function of their EROI, i.e. that those sites offering the best energy returns are exploited first, then we may now re-plot the cumulative distribution function as EROI depletion as a function of exploitation, i.e. production by rotating the axes and ranking the sites by EROI from highest to lowest, as shown in Figure Figure 4-6.

Another possibility for the shape of the physical component of the EROI function is a linearly decreasing function. This possibility will be tested in Section 9.3 and the results compared with the exponential function presented above.

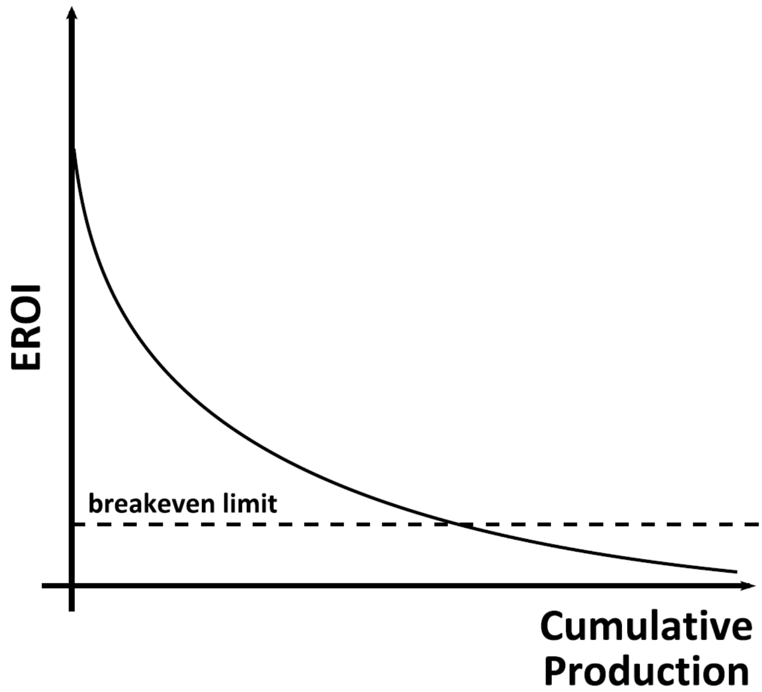


Figure 4-4. Physical component of EROI function.
EROI of the resource declines as more accessible resources are exploited and production turns to those resources offering lower energy returns.

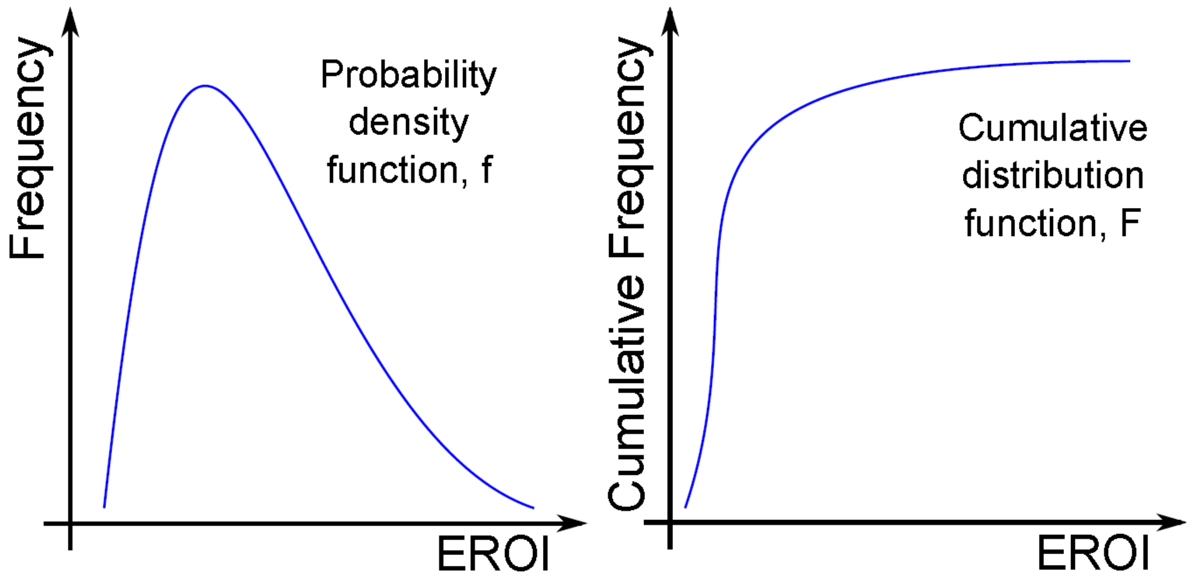


Figure 4-5. Probability density function and cumulative distribution function for EROI of an energy resource.

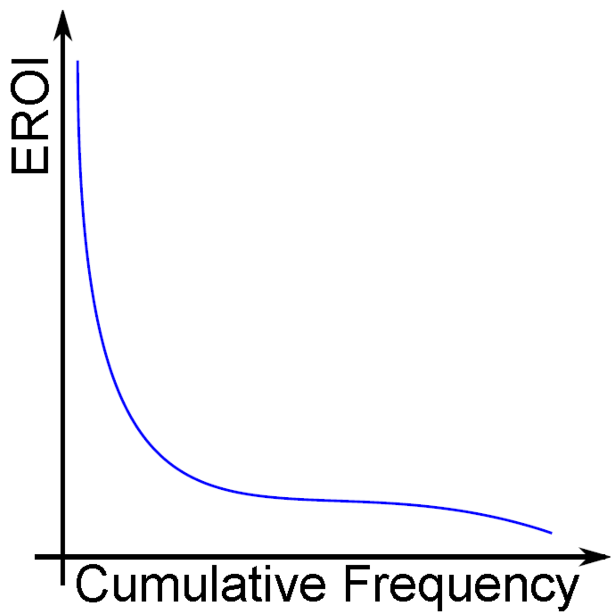


Figure 4-6. Decline of EROI of energy resource due to exploitation of best resources.

4.1.3. Finding P_{max}

Since the EROI function is a well-behaved function, the point P_{max} may be found via differentiation. P_{max} occurs at the value of $\boldsymbol{\rho_k}$ at which $\frac{d}{d\rho_k}[EROI_k(P_{max})] = 0$. Using the product rule finds that:

$$\frac{d}{d\rho_k}EROI_k = \frac{d}{d\rho_k}[\varepsilon_k F(\rho_k)] = \frac{d}{d\rho_k}[\varepsilon_k G(\rho_k)H(\rho_k)]$$

$$\Rightarrow G(\rho_k)\frac{dH}{d\rho_k} + H(\rho_k)\frac{dG}{d\rho_k} \qquad [4\text{-}6]$$

Differentiating ***G*** and ***H***:

$$G(\rho_k) = 1 - \Xi_k e^{-\xi_k \rho_k} \Rightarrow \frac{dG}{d\rho_k} = \Xi_k \xi_k e^{-\xi_k \rho_k} \qquad [4\text{-}7]$$

$$H(\rho_k) = \Phi_k e^{-\phi_k \rho_k} \Rightarrow \frac{dH}{d\rho_k} = -\Phi_k \phi_k e^{-\phi_k \rho_k} \qquad [4\text{-}8]$$

Substituting [4-7] and [4-8] into equation [4-6] obtains:

$$\left(1 - \Xi_k e^{-\xi_k P_{max}}\right)\left(-\Phi_k \phi_k e^{-\phi_k P_{max}}\right) + \left(\Phi_k e^{-\phi_k P_{max}}\right)\left(\Xi_k \xi_k e^{-\xi_k P_{max}}\right) = 0$$

$$\Rightarrow \Xi_k \Phi_k (\phi_k + \xi_k) e^{-\xi_k P_{max}} e^{-\phi_k P_{max}} = \Phi_k \phi_k e^{-\phi_k P_{max}}$$

$$\Rightarrow \Xi_k (\phi_k + \xi_k) e^{-\xi_k P_{max}} = \phi_k \qquad [4\text{-}9]$$

Taking the natural logarithm of [4-9] obtains:

$$\ln\left(\Xi_k(\phi_k + \xi_k)\right) - \xi_k P_{max} = \ln(\phi_k)$$

$$P_{max} = \frac{\ln(\Xi_k) + \ln(\phi_k + \xi_k) - \ln(\phi_k)}{\xi_k} \qquad [4\text{-}10]$$

4.1.4. The EROI function for renewable resources

Unlike non-renewable sources, for which the EROI is solely a function of cumulative production, in the case of renewable energy sources the physical component of EROI is a function of annual production.[19] In this case a reduction in production means that the EROI may 'move back up the slope' of this physical component. In the interim, technology, which is a function of cumulative production, will have increased, further pushing up energy returns. This entails that the EROI of a renewable energy source is a path dependent function of production.

Decline in the physical component of EROI for renewable energy sources represents the likelihood of the most optimal sites being used earliest. For example, deployment of wind turbines presently occurs only in sites where the average wind speed is above some lower threshold and that are close to large demand centres to avoid the construction of large distribution networks. Over time, the availability of such optimal sites will decrease, pushing deployment into sites offering lower energy returns, which should be reflected in declining capacity factors over time.

4.2. Supporting evidence

We provide supporting evidence for the EROI function presented by considering wind and solar resources for the US as a case study. The technological component of the EROI may be increased by the production of wind turbines that are able to better extract energy from the passage of air. This increase is subject to an absolute physical limit represented by the Lancaster-Betz limit (Rauh & Seelert, 1984) which defines the maximum proportion of energy that may be extracted from a moving column of air as $\frac{16}{27} \cong 60\%$. Experience curves for wind farms show that long-term costs of energy production from wind have fallen exponentially as a function of cumulative energy production (a proxy for 'experience') (Junginger et al., 2005).

The resource base for wind has been extensively (and intensively) mapped in several regions of the world. The National Renewable Energy Laboratory (NREL) Western Wind Dataset (NREL, 2010a) was used to produce a depletion curve of the US wind resource, ranked by power density (W/m^2) shown in Figure 4-7. The power density of the wind resource

[19] The technological component will still be a function of cumulative production, which serves as a proxy measure of experience.

initially declines exponentially as a function of land area, before dropping sharply below $500\ W/m^2$.

NREL have also produced the National Solar Radiation Database (NSRDB), for the mainland US (NREL, 2010b). This data was used to produce a depletion curve of the US solar resource ranked by energy flux density ($Wh/m^2/day$) shown in Figure 4-8. The energy flux density of the solar resource declines exponentially as a function of total land area from a maximum of just over 8,000 $Wh/m^2/day$.

Brandt (2010) has made a long-term study of the EROI of oil production in California between 1955 and 2005. The EROI of this oil at the mine-mouth is shown in Figure 4-9. An exponentially decreasing curve is shown for comparison. The initial decline is greater than exponential.

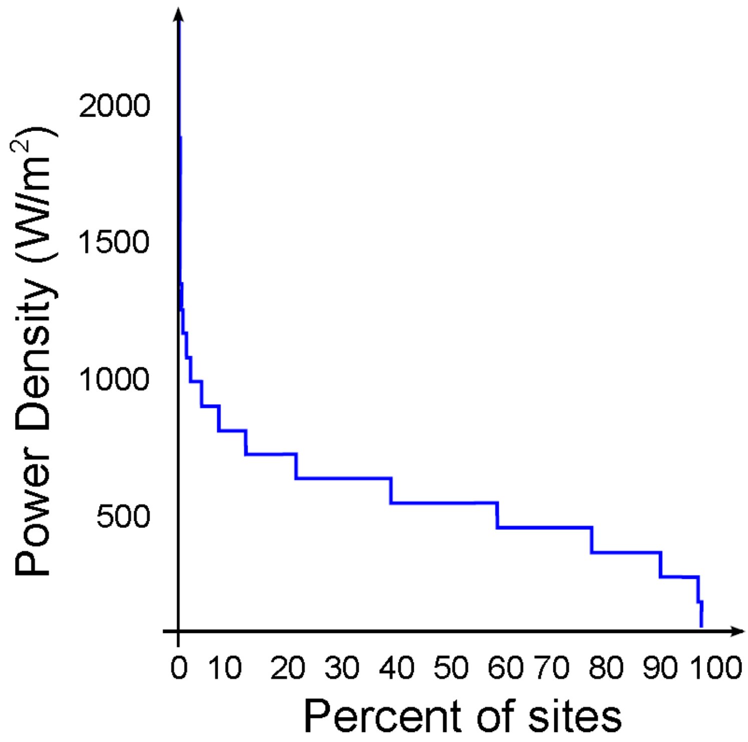


Figure 4-7. Depletion curve for the wind resource in the United States.
Ranked by power density (W/m^2) as a percentage of total land area. The quality of the wind resource decreases exponentially.

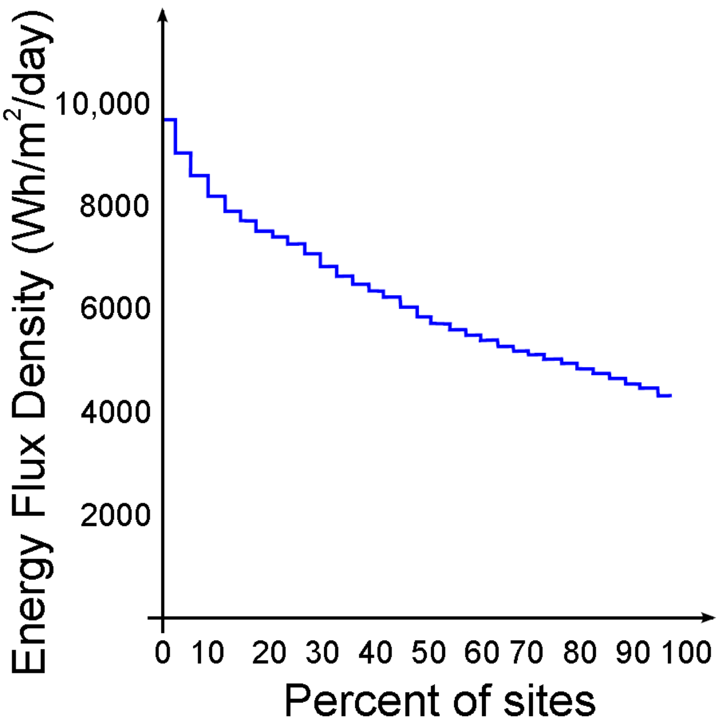


Figure 4-8. Depletion curve for the solar resource in the United States.
Ranked by energy flux density ($Wh/m^2/day$) as a percentage of total land area. The quality of the solar resource decreases exponentially.

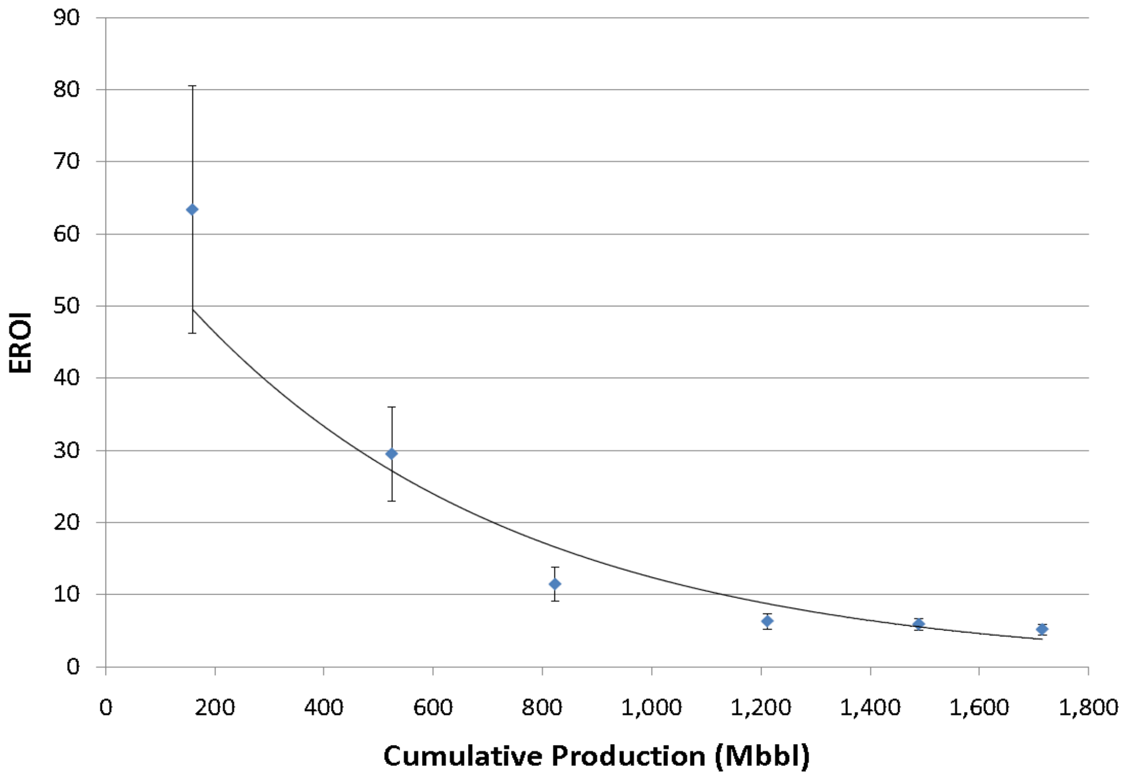


Figure 4-9. EROI at the mine-mouth plotted as a function of cumulative production for California oil production between 1955 and 2005.
An exponential curve is plotted for comparison. The EROI initially declines greater than exponentially.

CHAPTER 5. GLOBAL ENERGY MODELLING: A BIOPHYSICAL APPROACH (GEMBA)

5.1. A biophysical systems view of the energy-economy system

The energy-economy system is considered as a thermodynamically open system (i.e. open to flows of both energy and materials). The system has a closed-loop feedback control structure allowing it to be self-regulating, i.e. the system is able to maintain its own pattern of organisation. Due to the presence of these feedback loops, the energy economy system is highly complex and non-linear in behaviour; hence it must be modelled via numerical simulation, since to attempt an analytical solution would prove too difficult.

Energy supply defines the absolute limit on all social and economic activity since, "the dynamics of the economic process are ultimately constrained by the availability of energy in the environment and its accessibility to economic consumption" (P.S. Bodger & Baines, 1988, p. 2). Growth of the system relies on the creation of infrastructure capable of exploiting energy flows within the environment.

An energy circuit model of the global economy according to Gilliland (1975) is pictured in Figure 5-1. The system is reduced to two main sectors: the energy transformation sector and the main economy. The energy sector, in response to a demand for processed energy **D** from the main economy, processes energy resources (wind, coal, crude oil, etc.), of amount **R**, into forms useable by the rest of the economy[20]. The main economy uses this energy to perform all functions, including the fabrication of physical capital. To achieve its ends, the energy sector requires some 'subsidies': process energy, $\mathbf{S_1}$, which it is assumed to take before the flows

[20] Demand for raw energy **R** must be greater than the demand for processed energy **D** to account for losses during processing.

reach the rest of the economy; and some physical capital, $\mathbf{S_2}$, delivered from the output of the main economy.

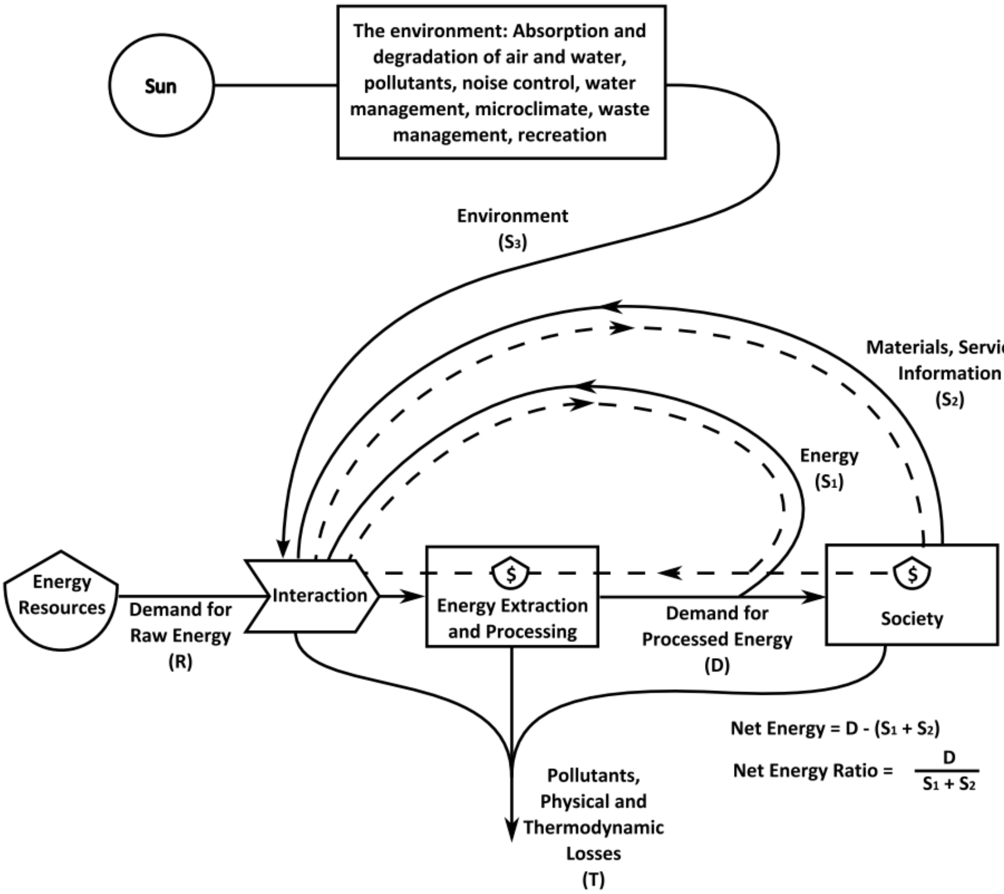


Figure 5-1. Categorisation of energy subsidy types and the counter-current relation of dollar flow to energy flow from (Gilliland, 1975).
Solid lines represent energy flow and dashed lines represent dollar flow. In response to demand for processed energy D, the energy sector extracts raw energy R and processes it (incurring losses T) for the main economy. To meet this end the energy sector requires energy S_1 and physical capital S_2 in return. Money is exchanged in human-to-human interactions, but serves no purpose in human-to-nature exchanges.

Distinction is made between those energy resources which are limited in total amount and those that are unlimited in total but are strictly limited in terms of their energy flux. The former are environmental stock resources, often called *non-renewable*, such as coal or uranium; the latter are environmental flow resources, often called *renewable*, such as wind or hydro. Two commonly used energy resources stand somewhere between these two categories. Strictly speaking, biomass in the form of living plants constitutes an environmental stock resource however, since the stock may be regenerated on timescales of decades, or even years, it has been decided to classify biomass as renewable. The geothermal resources is also degraded by its use, and a particular resource, such as a specific field, may be degraded to such an extent as to be of no further use. Despite this, the global resource, due to heat from the Earth's core, is in no danger of being degraded in total (only in local availability); hence the total resource shall also be considered renewable.

The surplus energy produced by the energy sector (the amount of energy delivered to the main economy, less the amount expended in extraction and processing), is known as the *net energy yield*, $\mathbf{N} = \mathbf{D} - (\mathbf{S_1} + \mathbf{S_2})$. This surplus is dependent on a number of other factors. The first factor is the magnitude of energy resources existing for exploitation, which shall be called the ***availability*** (P.S. Bodger & Baines, 1988; P. S. Bodger, et al., 1989; N. J. Peet, 1986). In the case of non-renewable resources, this shall be represented by the *ultimately recoverable resources* (URR) (William D. Nordhaus, 1974), in the case of renewable resources this shall be represented by the *technical potential* (TP) (Graßl et al., 2004). The second factor is the ***accessibility*** of the energy resource, as represented by the EROI ratio. The third factor is the stock of energy sector capital, sometimes called the *installed* or *production capacity* in the case of renewable energy sources (J. Edmonds & Reilly, 1985; WEA, 2000). The fourth factor determining the net energy yield is the proportion of subsidies in the form of physical capital subsidies, $\mathbf{S_2}$, to the total subsidies received, $(\mathbf{S_1} + \mathbf{S_2})$ which shall be called the ***capital intensity*** of the energy source. For example, electricity from photovoltaic (PV) cells requires almost no process energy, hence it is much more capital intensive than electricity generated from coal.

5.2. Methodology

This section outlines the methodology for the GEMBA model; the contribution of this thesis. The energy-economy system is considered to be a dynamic system. Dynamic systems are characterised by their complex nature, with many interacting causal and feedback loops that must be analysed at the systems level; they cannot be decomposed into simpler elements or processes. Due to the existence of feedback loops, none but the simplest complex dynamic systems may be fully understood analytically (as discussed in Section 2.1), hence, these systems must be studied through numerical simulation. A number of steps assist in the definition of a model system (Albin, 1997; Tonelli, 2007):

1. Define system scope and boundary
2. Identify most important stocks and flows
3. Identify other factors that affect stocks and flows
4. Identify main feedback loops
5. Model structure diagram

6. Define assumptions explicitly
7. Determine equations describing physical behaviour
8. Simulation

The next sections deal with each of these steps in turn.

5.2.1. Define system scope and boundary

There are two steps which assist in the identification and classification of a system's scope and boundary (Sauter, 2008). The first step concerns inputs and outputs of the system: what are the essential outputs of the system; what transformations are necessary to produce these outputs and; what inputs are necessary for the transformations to take place?

In the case of the energy-economy system, the essential output of the system is human-made capital, such as cars, buildings, clothes, etc., which shall be called INDUSTRIAL OUTPUT. The transformations necessary to produce these outputs are the processing of energy resources into useable forms by the energy sector and the subsequent 'consumption' or degradation into unusable form, by the industrial sector. Other resources, such as minerals, water, etc. necessary for the output shall be ignored. As such the necessary inputs to the system are the energy resources.

Since the system is being characterised purely in terms of physical attributes, the subsystems (the energy sector and the main economy) shall consist of a number physical elements:

- ENERGY SECTOR CAPITAL STOCK [EJ] — the infrastructure for energy production (oil rigs, wind turbines, hydro dams, etc.) in terms of their embodied energy;
- TOTAL and NET ENERGY YIELDS [EJ/yr]— the energy flows to the rest of the economy;
- INDUSTRIAL SECTOR CAPITAL STOCK [EJ] — the infrastructure of the rest of the economy (factories, buildings, roads, etc.) in terms of their embodied energy and;
- INDUSTRIAL OUTPUT [EJ/yr] — the physical capital output of the rest of the economy.

The scope of the model is defined by the research question, "can renewable energy sources support current levels of energy consumption?" Population is not considered within the model for two reasons. Firstly, the research question regards only total energy consumption, as opposed to *per capita* consumption. Secondly, only exosomatic energy sources are considered significant to economic activity. As such, flows of food are not considered within the renewable energy sources, since these flows have to be maintained simply to support the population, whatever level of economic activity is undertaken. Since agriculture is external to the scope of the model, consideration of population is also unnecessary.

Omitting population runs contrary to the standard economic energy modelling approach which (usually) determines energy demand as the product of population and *per capita* energy demand. The use of *per capita* (i.e. average) energy demand does not show the distribution of energy use over the population. These inequalities are exacerbated when considering a non-regionalised, global system. How the distribution of energy consumption will evolve over time will depend upon many interacting social factors. These are outside the scope of the GEMBA model.

Within the GEMBA model energy demand can be modelled in two ways: exogenously, using a logistic growth curve wherein energy demand is a function of time and; endogenously, where energy demand is a function of the economic (physical) capital stock, i.e. the amount of industrial and consumer goods. This endogenous demand function assumes that there is a positive correlation between the number of goods and the energy consumed. The justification for this assumption is that some proportion of the goods produced will be energy-consuming, e.g. electrical devices, vehicles, etc.

5.2.2. Identify important stocks and flows

Within system dynamics modelling, a distinction is made between stocks (sometimes called levels) and flows (sometimes called rates). Stocks are increased by inflows and decreased by outflows. The level of the stock represents the accumulation or integration over time of the flows entering and leaving them. A simple example consists of a bath, wherein the taps allow a certain flow of water into the bath and the plug hole allows a certain rate of water to drain out. The stock of water within the bath at any time, $\boldsymbol{t}$, represents the initial stock of water at time $\boldsymbol{t} = 0$ plus the integration of the water flowing in through the taps, less the water flowing out through the plug-hole over all time = $0 \rightarrow \boldsymbol{t}$.

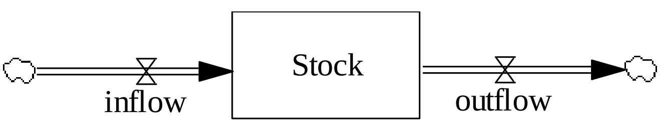


Figure 5-2. Simple stock and flow diagram.
The level of the stock variable will be dependent on the rate of the inflow and outflow.

Stocks

All stocks within the model are measured in EJ. Important physical stocks include:

- ENERGY SECTOR CAPITAL STOCK — infrastructure or capital stocks for each energy source;
- INDUSTRIAL CAPITAL STOCK — the capital stock of the rest of the economy and;
- ULTIMATELY RECOVERABLE RESOURCES (URR) — the total recoverable stock of non-renewable energy sources.

The non-renewable energy sources included within the model are:

- COAL
- CONVENTIONAL OIL
- CONVENTIONAL GAS
- UNCONVENTIONAL OIL
- UNCONVENTIONAL GAS
- URANIUM (assuming 'burner' reactor)

A distinction is made between 'conventional' and 'unconventional' sources of oil and gas to reflect the different EROI of the sources. UNCONVENTIONAL OIL includes such sources as natural gas liquids (NGL), polar, deep water and heavy oils, as well as oil from tar sands and oil shale. UNCONVENTIONAL GAS includes coal-bed methane, shale gas and tight gas. Methane hydrates were not considered due to lack of reliable data.

Flows

All flows within the model are measured in EJ/yr. Important flows are:

- ACCUMULATION OF ENERGY SECTOR CAPITAL and ACCUMULATION OF INDUSTRIAL CAPITAL — the rate of accumulation of all capital stocks including all energy sectors and the rest of the economy;
- DEPRECIATION OF ENERGY SECTOR CAPITAL and DEPRECIATION OF INDUSTRIAL CAPITAL — the rate of depreciation of all capital stock including all energy sectors and the rest of the economy;
- ANNUAL ENERGY PRODUCTION — the rate of of energy sources;
- TECHNICAL POTENTIALS (TP) — the recoverable flows of each of the renewable energy sources.

Renewable energy sources included within the model are:

- BIOMASS
- HYDRO
- GEOTHERMAL
- TIDAL
- WIND
- SOLAR
- WAVE
- OCEAN THERMAL ENERGY CONVERSION (OTEC)

All of the renewable energy sources are either currently in commercial operation (biomass – solar) or, in the case of wave and OTEC, in late development phase with test plants and commercial operation expected to start within the next few decades (WEC, 2007). Where a resource may be used directly for heat or used to generate electricity, such as geothermal and solar, direct use has not been considered due to lack of data.

The availability of energy resources is represented by ULTIMATELY RECOVERABLE RESOURCES, in the case of non-renewable resources, and TECHNICAL POTENTIALS, in the case of renewable resources. These are input parameters that may be altered by the user or varied for sensitivity testing or calibration. A literature review of available resources for each of the energy sources used by the model has been conducted to ensure that the values used in the model accurately reflect current knowledge (see Section 6.3)

5.2.3. Identify other factors that affect stocks and flows

A number of other factors affect the principal stocks and flows within the energy-economy system. These include:

- INCEPT DATE [yr] — the year in which a particular energy source enters the market place[21];
- the EROI of each energy source[22] which is a dynamic function of two factors (as discussed in CHAPTER 4):
    - the peak EROI value for each energy source

[21] Or, perhaps more accurately, the date that a particular energy source first gains a pre-defined share, say 1%, of the energy market

[22] The accessibility and availability of an energy resource are closely related within the model. It is assumed that the entirety of the available resource is also accessible and that the accessibility of the resource approaches the breakeven limit of one as the availability approaches zero.

    - the proportion of the available resource currently under production or having been produced;
- CAPITAL FACTOR — the ratio of energy subsidy in embodied as capital to the total input of each energy source.
- LIFETIME of all capital stock (assumed constant for all capital stock and given a nominal value of 20 years)[23];
- the ***allocation*** of total energy demand to each energy source (which is defined purely in physical terms as opposed to a price-based allocation method) and;
- the ***demand*** for energy in EJ/yr, which is defined endogenously as a function of three factors:
    - the level of the INDUSTRIAL CAPITAL STOCK
    - the ***energy intensity*** of the main economy, that is the ratio of INDUSTRIAL OUTPUT to NET ENERGY YIELD;
    - the CAPITAL EFFECTIVENESS of the main economy, that is the rate of INDUSTRIAL OUTPUT per unit of INDUSTRIAL CAPITAL STOCK

The INCEPT DATE of an energy source defines the time at which the technology of society is able to take advantage of that energy source. The incept date does not reflect the date at which that energy source was first harnessed for human purposes, for instance there is evidence to suggest that coal has been used since Palaeolithic times (Théry, Gril, Vernet, Meignen, & Maury, 1996) and wind has been used for power for at least two millennia as a source of propulsion for sail boats. Rather, the incept date signals the time at which modern use of the energy source achieved a significant share of total global energy production. As such, over the time horizon of investigation from 1800 to 2200, both biomass and coal have been in use from the beginning. They were joined by conventional oil sometime around 1860, natural gas around 1880, and hydro-electricity around 1895 (Etemad & Luciani, 1991). The 20th Century saw the introduction of geothermal for electricity in 1954, tidal in 1960, and wind and then solar in the seventies. Within the GEMBA model, INCEPT DATE is an input parameter that may be changed by the user or varied for sensitivity testing or calibration.

The EROI function used in the model is an explicit, dynamic function of energy production, as opposed to the implicit or static function used in previous biophysical energy models (P.S. Bodger & Baines, 1988; M. Slesser, 1992). The function has two variables: PEAK EROI and

[23] The assumption of a 20 year lifetime for all capital stock is something of a simplification. The value of 20 years was chosen as a base as this is a standard economic ‘lifetime’ often used to convert energy payback time (the time taken for an energy source to produce as much output as was used in its manufacture) into EROI values.

either the ratio of CUMULATIVE PRODUCTION to ULTIMATELY RECOVERABLE RESOURCES in the case of non-renewable energy sources or of ANNUAL PRODUCTION to TECHNICAL POTENTIAL in the case of renewable sources. Hereafter this ratio is referred to as the EXPLOITED RESOURCES.

A literature review of estimates of EROI for each of the energy sources used by the model has been conducted, again to ensure that the values used in the model accurately reflect current knowledge (see Section 6.1).

The concept of capital intensity, as represented in the model by the variable CAPITAL FACTOR, is necessary to determine the relationship between ENERGY SECTOR CAPITAL STOCK and the ANNUAL ENERGY PRODUCTION of each energy source. The EROI ratio represents the relationship between energy output (i.e. the amount of energy produced) for a given input of energy, in the form of capital and process energy. The CAPITAL FACTOR, i.e. the proportion of total energy put into the process in the form of physical capital, allows the total production over the lifetime of the capital (total energy output) to be determined from the EROI and the ENERGY SECTOR CAPITAL STOCK[24].

Since the model is composed entirely of physical units, there are no prices assigned to energy production via various energy sources. This prohibits the use of a price-based allocation function to apportion total energy demand between the different energy sources. As such, an allocation function based on entirely physical factors had to be developed. The allocation function used is based on the concept of energy cost hence reflecting energy theories of value (Alessio, 1981; C. A. S. Hall, Cleveland, & Kaufman, 2008; Liu, et al., 2008). The function is a product of two variables: EROI and EXPLOITED RESOURCES.

Within the model, energy demand is an endogenous function of INDUSTRIAL CAPITAL STOCK, CAPITAL EFFECTIVENESS and energy intensity, as represented by the variable ENERGY REQUIREMENT RATIO. The variable capital effectiveness is a measure of the INDUSTRIAL OUTPUT per unit of INDUSTRIAL CAPITAL STOCK. That is, it is a measure of the proportion of INDUSTRIAL CAPITAL STOCK that is itself capable of producing INDUSTRIAL OUTPUT and the productive capacity of that proportion.

Energy intensity of the economy is a measure of INDUSTRIAL OUTPUT per unit of NET ENERGY YIELD; that is the proportion of NET ENERGY YIELD which is embodied as INDUSTRIAL OUTPUT in the form of physical capital, as opposed to being used for other purposes, such as residential heating, personal transport, etc. This ratio cannot be greater than one, since this

[24] It is assumed that the output of a unit of capital is constant over the lifetime of that capital, i.e. that total output [EJ] = annual output [EJ/yr] × lifetime [yrs].

would be physically impossible. An ENERGY REQUIREMENT RATIO of one would mean that every unit of NET ENERGY YIELD entering the economy was being used in the process of production of INDUSTRIAL OUTPUT, i.e. physical capital, and none was being used for ancillary purposes. The variable ENERGY REQUIREMENT RATIO is not a measure of the efficiency of energy use. Such a measure would not be possible since energy is the only metric used within the model. To measure efficiency would require having another measure of INDUSTRIAL OUTPUT, say tonnes/yr, with which to compare changing embodied energy values. For example, knowing that the INDUSTRIAL OUTPUT changed from 600 to 500 EJ/yr does not indicate whether or not the efficiency increased; knowing that INDUSTRIAL OUTPUT changed from 6 MJ/tonne/yr to 5 MJ/tonne/yr, allows a calculation of the efficiency of energy use to be made.

Within the GEMBA model, the parameter, SMOOTH TIME, attempts to capture the delay in decision-making and response to market signals seen in the real-world energy-economy system by taking a time-average of previous values of the model variable, FAVOURABILITY. The parameter, SMOOTH TIME, has been set to a value of 20 years. However, in the case of the nuclear industry, each plant has a long lead-time of consent application and processing, planning and construction, which can take over twenty five years (Roques, Nuttall, Newbery, & De Neufville, 2006). Hence the GEMBA model may overestimate the flexibility in capital accumulation and depreciation.

5.2.4. Identify main feedback loops within the system

Dynamic systems are characterised by the existence of feedback loops wherein behaviour of a variable is a function of its own behaviour. Such feedback loops can operate as either virtuous or vicious circles amplifying or damping certain behaviour. Amplifying loops are referred to as positive feedback loops and damping loops as negative feedback loops.

Within the energy-economy system the main feedback loop runs through the energy and industrial sectors. As NET ENERGY YIELD increases, so too can INDUSTRIAL OUTPUT which in turn may be re-invested back into the energy and industrial sectors thus increasing the potential output of the energy sector and thence the output of the industrial sector. This loop may be either amplifying or damping. If NET ENERGY YIELD is constrained, this will potentially constrain INDUSTRIAL OUTPUT and re-investment of capital into both the industrial and energy sector. The effect of this lack of investment may be further decline in NET ENERGY YIELD.

The other main feedback loop within the system exists between ENERGY YIELD and EROI. Energy production causes a change in the EXPLOITED RESOURCES and hence a change in EROI which then affects the required ENERGY SECTOR CAPITAL STOCK needed to deliver a certain level of ENERGY DEMAND and thus affect the ACCUMULATION OF ENERGY CAPITAL. This may limit the INDUSTRIAL OUTPUT that is available for re-investment as ACCUMULATION OF INDUSTRIAL CAPITAL since energy sector needs are assumed to take priority. This will in turn affect the level of INDUSTRIAL CAPITAL STOCK and thereby influence ENERGY DEMAND.

There are many other such loops within the energy-economy system. The attempt to capture the majority of such interactions is aided by the creation of a causal loop diagram of the whole system.

5.2.5. Model structure diagram

The basic structure of the energy-economy system is pictured as an energy circuit diagram in Figure 5-3. Within the energy circuit scheme arrows represent energy flows with attendant losses 'to earth' as heat, etc. Energy 'losses' from the industrial sector include any energy consumed in activities that do not directly contribute to the production of physical capital, such as residential heating, lighting or energy for cooking.

The system is composed of two sectors: the energy and industrial sectors.[25] The energy produced by the energy sector flows into the industrial sector where it is embodied as physical capital.

[25] Within the model the energy sector is disaggregated into six non-renewable and eight renewable sub-sectors, as listed in section 2.2. The energy sector is shown in Figure 5-3 in aggregated form for the sake of simplicity.

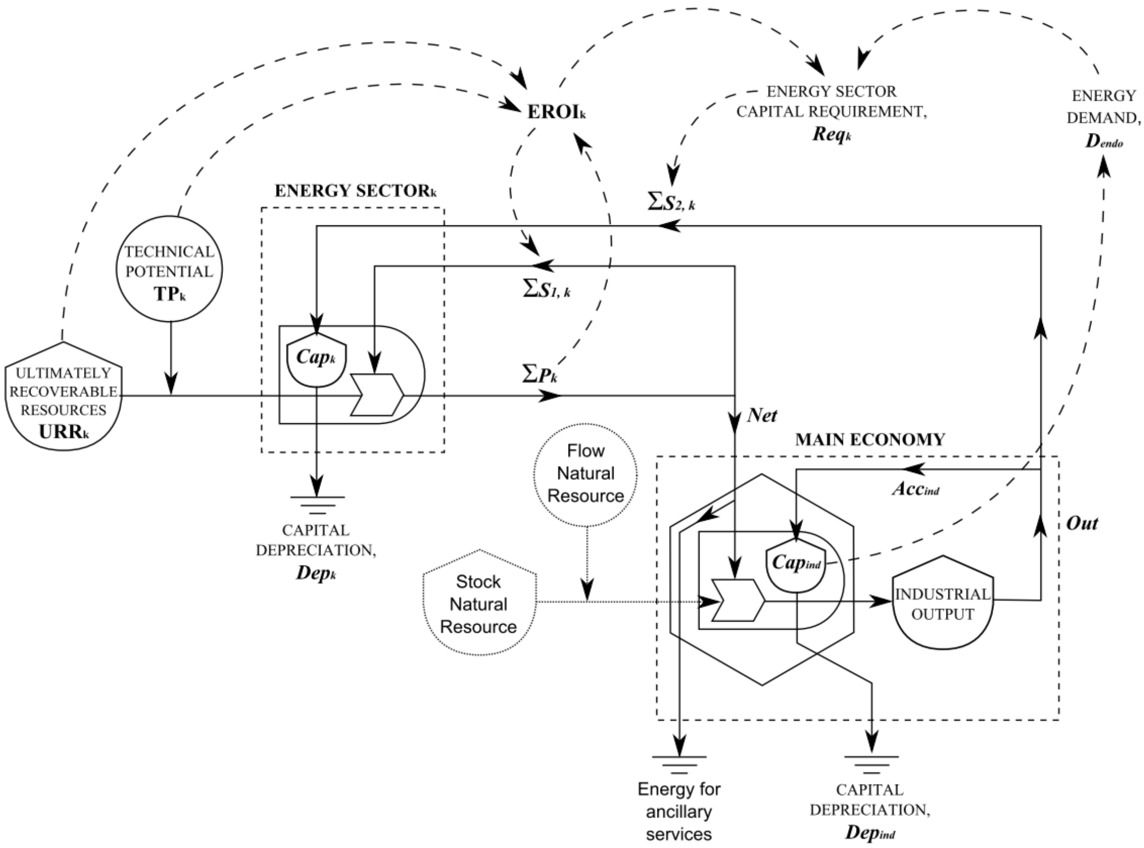


Figure 5-3. Structure of the energy-economy model as an energy circuit diagram.
All stages of energy production have been collapsed into a single process. Feedback is introduced into the system due to the values of energy S_1 and capital S_2 subsidies changing as a function of energy production. Bold arrows represent flows of energy and material, dashed arrows represent information flows. The dotted stocks and flows of natural resources are represented for completeness, but are not defined explicitly within the GEMBA model.

k = index of energy sub-sector

Cap = SECTOR CAPITAL STOCK [EJ]

Acc = ACCUMULATION CAPITAL STOCK [EJ/yr]

Dep = DEPRECIATION CAPITAL STOCK [EJ/yr]

χ = CAPITAL FACTOR [DMNL]

P = ANNUAL PRODUCTION [EJ/yr]

TP = TECHNICAL POTENTIAL [EJ/yr]

URR = ULTIMATELY RECOVERABLE RESOURCES

ρ = EXPLOITED RESOURCE [dmnl]

ε = PEAK EROI [dmnl]

L =LIFETIME OF CAPITAL STOCK [yr]

D = ENERGY DEMAND [EJ/yr]

γ = FAVOURABILITY [dmnl]

Req = REQUIRED CAPITAL STOCK [EJ]

S_1 = FUEL SUBSIDY [EJ/yr]

S_2 = CAPITAL SUBSIDY [EJ/yr]

Net = NET ENERGY YIELD [EJ/yr]

Out = INDUSTRIAL OUTPUT [EJ/yr]

ϵ = ENERGY REQUIREMENT RATIO [dmnl]

κ = CAPITAL EFFECTIVENESS [1/yr]

5.2.6. Define assumptions explicitly

> All that can be claimed for any model is that it be a "viable and effective method to reveal the implications of the primary assumptions about the nature of the world that went into it… These assumptions or 'pre-analytic visions' need to be made clear and placed in direct comparison with the corresponding assumptions of the alternatives." (Costanza, et al., 2007, p. 427)

Meadows et al. state, "a model is simply an ordered set of assumptions about a complex system" (1972, p. 20). In order to engage in any modelling process, be it quantum mechanical, economic or psychological, it is necessary to make a number of (more or less) arbitrary assumptions – "pre-analytic visions" – from which the consequences of the model may flow. Bearing in mind the above quotation from Costanza et al, the most important process is to make those assumptions explicit and open to discussion. This section outlines the major assumptions of the GEMBA model.

Following the work of Baines and Peet (1983) and also Bodger and Baines (1988) energy resources are characterised by three fundamental variables:

- INCEPT DATE**:** the year that the energy source first enters the market-place;
- AVAILABILITY**:** how much of each energy source is still available
- ACCESSIBILITY**:** the energy-return-on-investment (EROI) or energy yield ratio (EYR) offered by the energy source (hereafter referred to simply as EROI).

To these shall be added a fourth variable: capital intensity, as measured by the CAPITAL FACTOR.

Following the work of Costanza and Cleveland (1983) EROI is characterised by a peaking function dependent on EXPLOITED RESOURCES. It has been further assumed that this function is the product of a technological and a physical component. This function is explained in further depth in 0.

The distinction between the different energy carriers (liquid fuels, coke, electricity, etc.) and the variety of potential end uses (transport, space heat, process energy, etc.) is ignored within the GEMBA model. Energy demand is assumed to be for a homogenous 'energy', that is, energy sources are assumed to be perfectly substitutable, i.e. ENERGY DEMAND within the model is not specific to a particular energy source but rather just for energy, regardless of source or carrier.

The reason for this simplification concerns the long time frame of analysis and the availability of historical data. Over long periods of time, demand for certain energy services may be fulfilled by a variety of different energy carriers and energy sources. In the case of transport in industrialised nations, the past two hundred years have seen shifts from the use of biomass (in the form of horse and human feed) to coal for steam-trains and boats, to petroleum-based products for automobiles and diesel-trains and boats. Historical data over the period includes only total energy produced of each source (biomass, coal, oil, etc.). Any disaggregation made between various energy carriers and end use services would be an arbitrary assumption. Since the GEMBA model is calibrated using historical data, the use of any such assumptions constitutes circular reasoning – the model would be calibrated to the assumptions made.

Box 5-1. A note on energy quality

Energy resources come in many different forms, from primary product (be it solid liquid or gas) to secondary solid, liquid and gas fuels to energy stored chemically, physically or as heat and electricity. These different forms are said to be of different quality, reflecting the ease with which they may be put to use by society to achieve the various ends towards which they are directed.

Electricity is said to be the highest quality of energy due to its ability to perform a multiplicity of functions and its ease of distribution with few losses. At the other end of the spectrum energy stored as low-grade heat (below 100°C) is of a very low quality due to the inherent difficulties in directing the energy towards ends other than heating (which may be achieved, but only at low efficiencies even assuming a perfect Carnot engine).

Often the energy-return-on-investment (EROI) ratio attempts to reflect the quality of output of the process in question by introduction of a so-called *quality-correction factor* (N. Gagnon, Hall, & Brinker, 2009). This allows for comparison between technologies, such as hydro or wind turbines, that produce electricity directly and those, such as natural gas or coal, where electricity must be produced in power stations at much lower efficiencies (around 33%). Therefore, a hydro station producing 20 GJ of electricity per day with an EROI of 30 has an output actually equivalent to more like 60 GJ of primary energy (to account for the losses in primary energy usually encountered when producing electricity in thermal power stations) hence the EROI is actually 90. This convention is useful in portraying the preponderance of thermally generated electricity within our current system. However, it is not a convention that is adopted within the GEMBA methodology. The reason is, perhaps, best illustrated with an example.

The 20 GJ/day electrical output of a present-day hydro station may be worth around 60 GJ/day of coal directed toward the same end. the majority but not all coal is directed towards generating electricity. How should the comparison be made between the hydro-electricity and oil resources? Should it be assumed that the oil will be used to generated electricity at approximately 30% efficiency? Most oil is produced for transportation of individual vehicles. What is the quality factor in that case? Should comparison instead be made between the primary energy (hydro or oil) needed for running a vehicle? Should the (electric- and oil-driven) vehicles have to provide the same service? Must the electric vehicle have energy storage equivalent to a tank of fuel?

Further problems arise when we consider comparison over the long time scales used in the GEMBA methodology. Should the electrical output of a hydro station in the year 1900 still be compared with electricity from coal generated at 33% efficiency? What was the main use of coal at that time? What was the main end-use of energy at that time? Should hydro-electricity from 1900 be equivalent to hydro-electricity from the present day, given the greater efficiency of conversion to end-use in today's system?

Clearly there is no straightforward answer to these questions. Consideration of these issues has led to the decision to omit energy quality from the GEMBA methodology and compare thermal energy equivalents.

The distinct processing stages of the energy sector (extraction, transportation, refining, generation, distribution, etc.) have all been aggregated, since an embodied energy perspective takes all of these losses into account. The capital needs of the energy sector takes priority over those of the industrial sector, such that ACCUMULATION OF ENERGY SECTOR CAPITAL may come at the expense of maintaining INDUSTRIAL SECTOR CAPITAL.

Neither nuclear fission using 'breeder' reactors, nor nuclear fusion were considered as viable non-renewable technologies. Nuclear fusion was not considered viable due to ongoing problems, such as "ballooning costs and growing delays" (Brumfiel, 2009, p. 488), at the International Thermonuclear Experimental Reactor (ITER) test plant, and schedule and budget issues at the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory in the United States (Parkins, 2006). Fusion is unlikely to be practical as a source of energy before 2050 (Kokesh, 2006), furthermore, some authors believe that energy from fusion can never be economically competitive with other sources (Kokesh, 2006; Parkins, 2006; V. Smil, 2006).

Breeder reactors have also faced many problems in implementation, due to both safety issues and links with production of weapons-grade Plutonium, a product of the reaction (Lidsky & Miller, 2002). As of Feb 2010, the current status of breeder reactors worldwide is that two are under construction (one in India and one in the Russian Federation), one is operational, one is in the process of long-term shutdown and seven are shutdown (IAEA, 2008).

Nuclear reactors using Thorium were not considered due to difficulties in obtaining information regarding worldwide reserves of Thorium, or the potential of Thorium reactors.

5.2.7. Equations describing physical behaviour

In order to simulate the model numerically the relationships between variables must be defined mathematically.

As discussed previously in order to define ANNUAL PRODUCTION in terms of ENERGY SECTOR CAPITAL STOCK, ***Cap***, we need to know the EROI and the CAPITAL FACTOR, $\boldsymbol{\chi}$. EROI is defined as "the ratio of the gross amount of fuel extracted in the energy transformation process to the economic energy required to make that fuel available to society" (Charles A.S. Hall, et al., 1986, p. 28) . The total energy production of some unit of CAPITAL STOCK is the ANNUAL PRODUCTION multiplied by the LIFETIME, ***L***, of that CAPITAL STOCK[26]. The inputs can be divided between inputs embodied in the form of physical capital (capital inputs) and those as energy to run the production process (fuel inputs), such as operating or maintenance energy.

$$EROI_k = \frac{total\ energy\ output}{total\ energy\ input} = \frac{P_k L_k}{S_{1,k} + S_{2,k}} \qquad [5\text{-}1]$$

The model variable CAPITAL FACTOR, i.e. the ratio of capital inputs to total inputs, $\boldsymbol{\chi}$, may vary between energy sources; however the value will always be less than one.

$$X_k = \frac{S_{1,k}}{S_{1,k} + S_{2,k}} < 1 \qquad [5\text{-}2]$$

The annual production of a particular energy source, $\boldsymbol{P_k}$, can now be defined by combining [5-1] and [5-2] and re-arranging. Since EROI is defined for a constant ANNUAL PRODUCTION over

[26] More accurately the total energy output is the annual production integrated over the lifetime of the unit of capital stock, however, it is assumed that the annual output of each unit of energy capital stock will be approximately equal to the average output over the lifetime of the capital stock.

the whole LIFETIME of the ENERGY SECTOR CAPITAL STOCK, $\boldsymbol{L}$, the ANNUAL PRODUCTION is inversely proportional to the LIFETIME

$$P_k = \frac{Cap_k}{\chi_k}\frac{EROI_k}{L_k} \qquad [5\text{-}3]$$

Consequently, TOTAL ENERGY YIELD, $\boldsymbol{P_{total}}$, is the sum of ANNUAL PRODUCTION of all energy sources.

$$P_{total} = \sum_k P_k \qquad [5\text{-}4]$$

The variable EXPLOITED RESOURCES, $\boldsymbol{\rho}$, is a measure of how much of the energy resource is currently being produced, normalised with respect to the total available resource for that energy source. It is different for non-renewable (stock) and renewable (flow) energy sources.[27]

$$\rho_{k(renewable)} = \frac{P_k}{TP_k} \qquad [5\text{-}5]$$

$$\rho_{k(non-renewable)} = \frac{\int_0^t P_k dt}{URR_k} \qquad [5\text{-}6]$$

EROI of an energy source, $\boldsymbol{k}$, is a function of EXPLOITED RESOURCES of that energy source, $\boldsymbol{\rho_k}$, and is made up of two components: $\boldsymbol{G}$, an asymptotically increasing function, representing technological progression; and $\boldsymbol{H}$, an asymptotically decreasing function, representing declining resource quality. The function $\boldsymbol{F}$ is then scaled by a coefficient $\boldsymbol{\varepsilon_k}$, representing the maximum possible energy return of that energy source, PEAK $EROI_k$.

$$EROI_k = \varepsilon_k F(\rho_k) = \varepsilon_k G(\rho_k) H(\rho_k) \qquad [5\text{-}7]$$

$$G(\rho_k) = 1 - \Xi_k e^{-\xi_k \rho_k} \qquad [5\text{-}8]$$

$$H(\rho_k) = \Phi_k e^{-\phi_k \rho_k} \qquad [5\text{-}9]$$

ENERGY DEMAND is an endogenous function of three factors: INDUSTRIAL CAPITAL STOCK, $\boldsymbol{Cap_{ind}}$ [EJ]; the ENERGY REQUIREMENT RATIO, $\boldsymbol{\epsilon}$ [dmnl] and; the CAPITAL EFFECTIVENESS, $\boldsymbol{\kappa}$ [EJ/yr/EJ].

[27] Availability is negatively correlated with production. The more energy is produced from a resource the less is available. In the case of non-renewable (stock) resources this decline in availability is irreversible; in the case of renewable (flow) resources, it is reversible, so long as the resource has not been degraded.

$$D_{endo} = \epsilon\kappa Cap_{ind} \qquad [5\text{-}10]$$

ENERGY DEMAND may also be defined exogenously using a logistic growth function, which increases exponentially from an initial value $\boldsymbol{D_0}$, at rate $\boldsymbol{r}$, up to some limit $\boldsymbol{K}$, as a function of time, $\boldsymbol{t}$.

$$D_{exo} = \frac{KD_0e^{rt}}{K + D_0(e^{rt} - 1)} \qquad [5\text{-}11]$$

Once total ENERGY DEMAND, $\boldsymbol{D_{endo,\ exo}}$, has been identified, the proportion provided by each energy source, $\boldsymbol{D_k}$, must be determined. Since GEMBA is a purely physical model, a physical allocation function must be defined. Demand is assumed to be allocated due to the FAVOURABILITY of the energy source, $\boldsymbol{\gamma_k}$ (which can take a value between 0 and 1), which is a function of both EROI and EXPLOITED RESOURCES[28].

$$D_k = \gamma_k D \qquad [5\text{-}12]$$

$$\gamma_k = \frac{\rho_k EROI_k}{\sum_k \rho_k EROI_k} \qquad [5\text{-}13]$$

Once demand for a particular energy source has been allocated the CAPITAL STOCK required to produce that output, $\boldsymbol{Req_k}$, is defined by substituting demand for production in [5-3] and re-arranging.

$$Req_k = \frac{\chi_k D_k L_k}{EROI_k} \qquad [5\text{-}14]$$

The difference between REQUIRED ENERGY SECTOR CAPITAL STOCK, $\boldsymbol{Req_k}$, and existing ENERGY SECTOR CAPITAL STOCK, $\boldsymbol{Cap_k}$, determines the energy subsidy required by the energy sector, $\boldsymbol{S_{2,k}}$.

$$S_{2,k} = Req_k - Cap_k \geq 0 \qquad [5\text{-}15]$$

All CAPITAL STOCK (of both the energy and industrial sector) is diminished by DEPRECIATION OF CAPITAL STOCK.

$$Dep_{k,ind} = \frac{Cap_{k,ind}}{L_{k,ind}} \qquad [5\text{-}16]$$

[S] Since accessibility is itself a function of availability then allocation is a function purely of production, however, for the purposes of explication the above characterisation is simpler.

The amount of CAPITAL STOCK at time ***t*** is determined by integrating the ACCUMULATION and DEPRECIATION over all time up to ***t***. For a discrete time-step approach this is equivalent to the sum of the CAPITAL STOCK from the last time period and the net flow from the current period.

$$Cap(t) = \int_0^t \big(Acc(t) - Dep(t)\big)dt \Rightarrow Cap(t-1) + Acc(t) - Dep(t) \quad [5\text{-}17]$$

Some energy subsidy, $\boldsymbol{S_{1,k}}$, which must come from the TOTAL ENERGY YIELD of the energy sector before it reaches the rest of the economy, is required to operate the CAPITAL STOCK of the energy sector to enable the production of energy, $\boldsymbol{P_k}$.

$$S_{1,k} = (1 - \chi_k)\frac{P_k}{EROI_k} \quad [5\text{-}18]$$

The NET ENERGY YIELD from each energy sector, $\boldsymbol{Net_k}$, is the ANNUAL PRODUCTION less the FUEL FEEDBACK. It is important to note that this conception of NET ENERGY YIELD is different from usual net energy yield of energy analysis, which would be ANNUAL PRODUCTION less (FUEL FEEDBACK + CAPITAL FEEDBACK)

$$Net_k = P_k - S_{1,k} \quad [5\text{-}19]$$

TOTAL INDUSTRIAL OUTPUT is a quotient of the sum of NET ENERGY YIELD from all energy sectors with the energy intensity of the economy, represented by the ENERGY REQUIREMENT RATIO, $\boldsymbol{\epsilon}$.

$$Out_{total} = \frac{\sum_k Net_k}{\epsilon} \quad [5\text{-}20]$$

NET INDUSTRIAL OUTPUT is then TOTAL INDUSTRIAL OUTPUT less the TOTAL CAPITAL FEEDBACK required by the energy sector. This NET INDUSTRIAL OUTPUT is assumed to be re-invested back into the industrial sector as ACCUMULATION OF INDUSTRIAL CAPITAL.

$$Acc_{ind} = Out_{total} - \sum_k S_{2,k} \quad [5\text{-}21]$$

5.2.8. Simulation

The GEMBA model was simulated using VenSim, a software package for designing, constructing, simulating and analysing system dynamic models (Ventana, 1988-2008). An example is given to demonstrate the method by which VenSim simulates a model. Figure 5-4 is a reduced form of the GEMBA model consisting of only the energy sector. Due to the feedback loops attempting to solve the equations for all of the variables analytically would lead to problems of simultaneity. VenSim avoids this problem by specification of initial values for any stock variables for time, t = 0. These values are then used to compute the value of all other variables for time, t = 1, and then the value of the stock variables is recalculated. Written in Visual Basic, the model displayed in Figure 5-4 is written as in Figure 5-5

The model went through various design iterations. The energy sector was initially composed of just two sub-sectors: one renewable, one non-renewable. This was done for two reasons: firstly, to allow familiarity with the model to be gained with a less complex system; and secondly, that the model was originally constructed in VenSim PLE which has no function to allow subscripts, hence the construction of each of the fourteen sub-sectors of the energy sector was considered unnecessarily complicated.

The learning from the two sector model allowed the construction of the fully disaggregated model in VenSim Professional, which has subscript functionality.

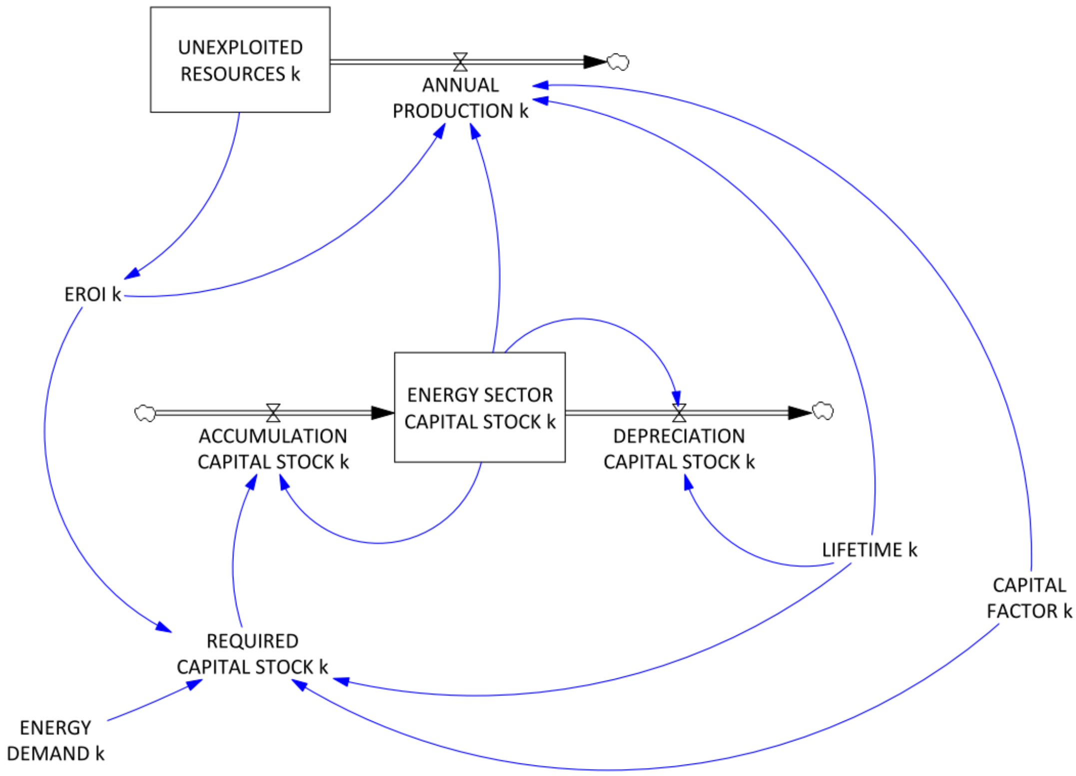


Figure 5-4 Diagram of a reduced form of the GEMBA model showing just one energy sector.
For this diagram, ENERGY DEMAND is assumed to be exogenous, since the industrial sector is not included. Boxes and pipes represent stocks and flows, respectively, of energy and materials. Curved arrows represent information flows.

```
Sub reduced_GEMBA()

    Dim n As Integer           'total number of timesteps
    Dim t As Integer           'time
    Dim lesc As Double         'lifetime energy sector capital (lesc)
    Dim cf As Double           'capital factor of energy sector (cf)
    Dim RER() As Double        'Remaining Energy Resources (RER)
    Dim aep() As Double        'annual energy production (aep)
    Dim EROI() As Double
    Dim ESCS() As Double       'Energy Sector Capital Stock (ESCS)
    Dim aesc() As Double       'accumulation energy sector capital (aesc)
    Dim desc() As Double       'depreciation energy sector capital (desc)
    Dim ed() As Double         'energy demand (ed)
    Dim escr() As Double       'energy sector capital requirement (escr)


    n = 100                    'set number of timesteps
    RER(0) = 100000            'initial value of RER
    ESCS(0) = 1                'initial value of ESCS
    lesc = 20                  'set capital stock lifetime
    cf = 0.9                   'set capital factor

    For t = 1 To n

        ed(t) = F(t)
        EROI(t) = G(RER(t - 1))
        aep(t) = ESCS(t - 1) * EROI(t) / cf / lesc
        RER(t) = RER(t - 1) - aep(t)
        escr(t) = cf * lesc * ed(t) / EROI(t)
        aesc(t) = Max(escr(t) - ESCS(t - 1), 0)
        desc(t) = ESCS(t - 1) / lesc
        ESCS(t) = ESCS(t - 1) + aesc(t) - desc(t)

    Next t

End Sub
```

Figure 5-5. The reduced GEMBA model, shown graphically in Figure 5-4, written as Visual Basic code. The functions F() and G() have not been defined.

CHAPTER 6. SUPPLEMENTARY DATA

The GEMBA model relies on a certain amount of historical energy production data in order to calibrate the model parameters: PEAK EROI, CAPITAL FACTOR, TECHNICAL POTENTIAL and ULTIMATELY RECOVERABLE RESOURCES of the various energy sources. Literature reviews have been conducted on estimates of the EROI, capital intensity, technical potential and ultimately recoverable resources in order to ensure that the values of these parameters, after calibration, align with current knowledge.

6.1. Analysis of EROI of energy sources

As discussed in Section 2.2 on Energy Analysis the EROI ratio defines the usefulness of an energy source by determining how accessible it is in producing energy for human purposes. A multitude of studies have been performed to analyse the EROI value of all of the major energy sources represented in the GEMBA model (see Appendix B for tables of data sources).

There have been many attempts to standardise the field of energy analysis. Initially, the International Federation of Institutes for Advanced Study (IFIAS) held the Energy Analysis Workshop on Methodology and Conventions (1974) and the IFIAS Workshop on Energy Analysis and Economics (1975) More recently, implementation of standards by the International Organisation for Standards (ISO) for both Life Cycle Assessment (LCA) principles and frameworks, ISO 14040 (2006), and LCA requirements and guidelines, ISO 14044 (2006). Unfortunately, there is still wide disparity in methodologies used for energy analysis (Mulder and Hagens, 2008) leading to difficulties in comparison of results due to incommensurability of measured quantities, as well as a wide range in results, as will be apparent in the large spread in the data for most energy sources. These problems are perhaps best summarised by Farrell et al. (2006, p.506)

> "It has long been recognized that calculations of net energy are highly sensitive to assumptions about both system boundaries and key parameter values. In addition, net energy calculations ignore vast differences between different types of fossil energy. Moreover, net energy ratios are extremely sensitive to specification and assumptions and can produce uninterpretable values in some important cases. However, comparing across published studies to evaluate how these assumptions affect outcomes is difficult owing to the use of different units and system boundaries across studies."

Another key issue is the paucity of data available. Some energy sources, such as biomass, have been studied intensely, whereas others have had very little investigation, even in the case of some mature technologies, such as hydro. Studies are often done on a 'site-by-site' basis, rather than being done at a regional or even global level. The data are also often 'static' estimates of a resource in a particular year, rather than tracking the resource over a number of years (although these 'dynamic' estimates have been carried out too, particularly in the case of oil).

Energy analysis studies are also very sensitive to the idiosyncrasies of the process under investigation.

Two oil producing sites may have very different EROI values due to a multitude of factors. These difficulties are compounded due to the difficulties of obtaining adequate data for a specific site, meaning that inputs often must be estimated using data from other sites.

The results of energy analysis studies are published in a wide variety of sources, including both peer-reviewed and non peer-reviewed works. The data are often also cited by others as secondary sources. In order to accommodate this, the data have been categorised by both primary (P)/secondary (S) and peer-review (PR)/non peer-reviewed (NP) source.

All of these factors combine to create large uncertainties in the energy analysis data. An important question to be asked is, "what is the relationship between the data presented in this chapter and the EROI function presented in CHAPTER 4?" In the case of those estimates where an analysis has tracked the EROI of a single resource over a number of years, the EROI function should give an approximate fit, within acceptable error margins as befits the (often large) uncertainty of the estimate. For example, the EROI function should be able to be fitted to the dynamic EROI data for the US, provided suitable parameter values are chosen. A fit between the EROI function and Brandt's (2010) EROI estimates for California oil is shown in Figure 6-1. Parameter values are listed in Table 6-1.

Table 6-1. Parameter values for fitting EROI function to Brandt (2010) data

URR (Mbbl)	Peak EROI	X	χ	Φ	ϕ
4688	99	0.10	2.98	1.00	10.52

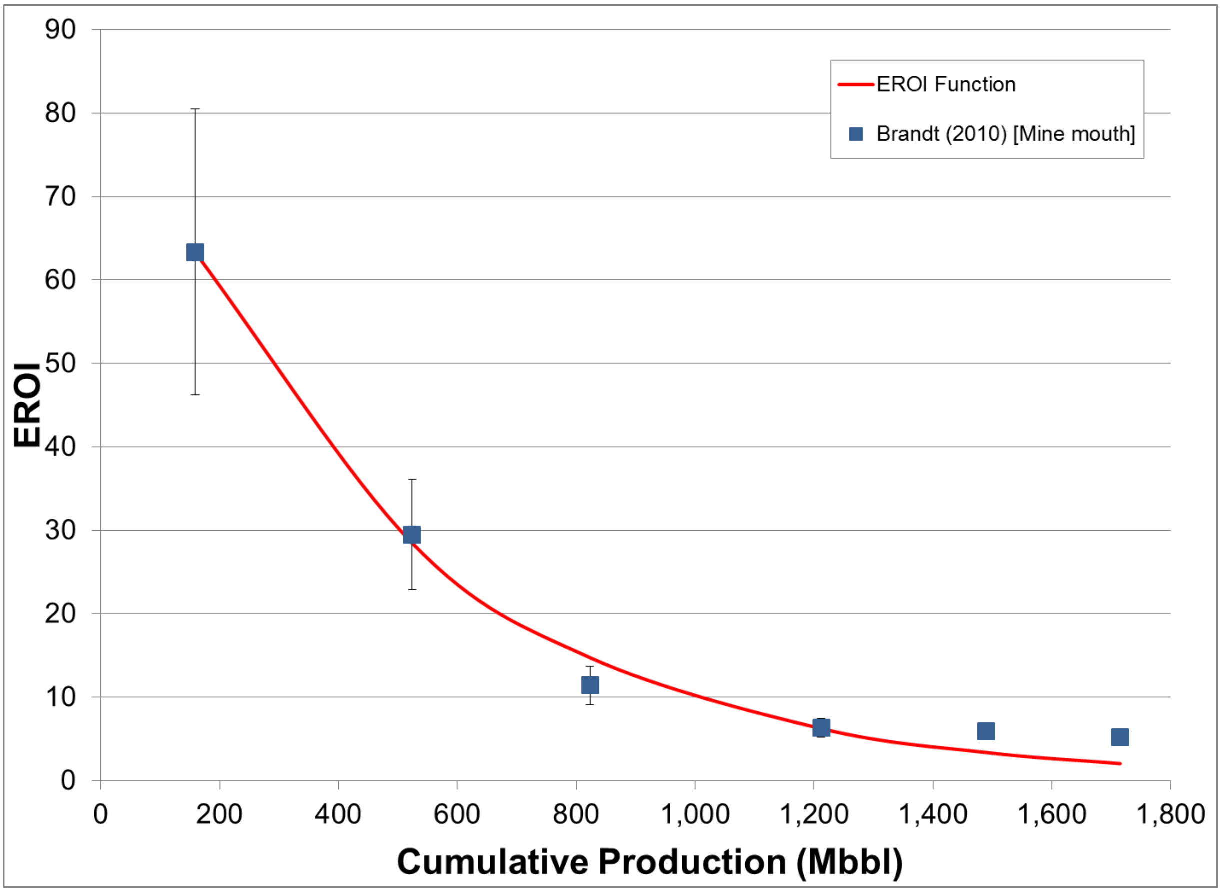


Figure 6-1 Fit between Brandt (2010) data and EROI function.

In the case of 'static' estimates made of one resource at one time, the link is very tenuous. There is little indication that the EROI function should be able to fit this data for all of the reasons outlined above:

- Studies of EROI range over a number of different resources, or the same resource over different regions;
- Studies may use different methodologies to calculate EROI;
- Studies may incorporate inputs and outputs using different means;

- Over short time periods, non-physical factors, such as price and extraction effort, may play a role in the EROI of a resource.

As such, these data will be used to give a broad approximation of the general state of globally aggregated EROI for each energy source. This uncertainty will be dealt with in the modelling stage by incorporating sensitivity analyses which sweep over much of the possibility space.

6.1.1. Non-renewable energy sources

Coal

This study found 112 estimates of the EROI of various processes involving coal production. These are categorised into five groups: dynamic estimates of a particular resource over time, static estimates of coal delivered to the economy, static estimates of electricity production using coal, coke and coal-to-X, X being either gas or liquid.

Looking first at the dynamic estimates of EROI (see Figure 6-2) it can be seen that the EROI of three coal resources are monotonically declining, whilst four are approximately constant or increasing up to a peak sometime around 1968 and thereafter decreasing. Only one estimate shows a monotonic increase over the period. This offers some support for the use of a peaking function for EROI.

Looking at the static estimates (see Figure 6-3), it can be seen that the only obvious trend in the data over time is a reduction in the value and number of estimates between 1980 and 1996. The range of EROI values for coal production from primary, peer-reviewed (PPR) sources is between 6 and 100. Smaller than the range when other sources are included. In general, products requiring further processing (coke, coal-to-gas and coal-to-liquid)[29] have lower EROI values.

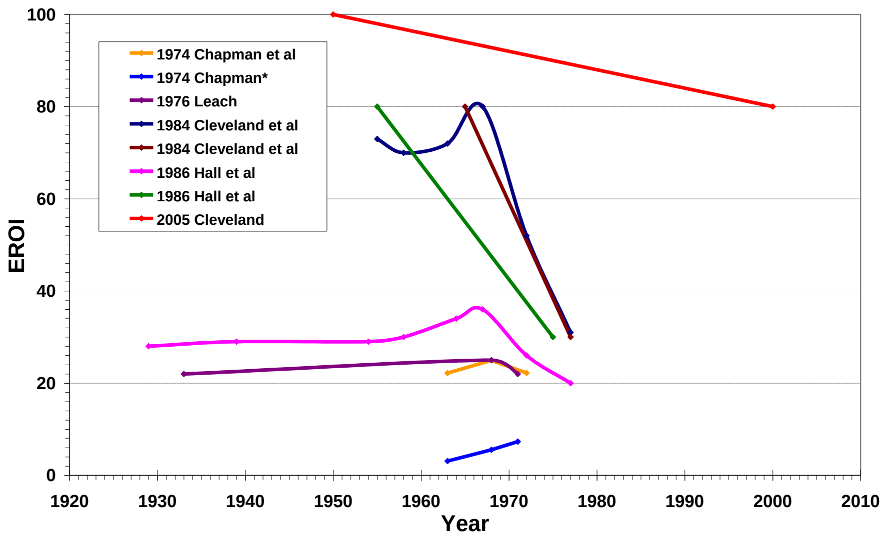


Figure 6-2. Dynamic estimates of EROI of coal production from various sources.[30]
Uses data from (P. F. Chapman, Leach, & Slesser, 1974), (Leach, 1976), (Cleveland, et al., 1984), (Charles A.S. Hall, et al., 1986), (Cleveland, 2005), *values for coke production taken from (Boustead & Hancock, 1979)

[29] In the plot these are combined as CtX, where X is either liquid (L) or gas (G).
[30] The discrepancy in estimates for (Cleveland el 1984; Hall et al 1986) is due to the inclusion or not of transportation costs from the mine to the point of use.

Figure 6-3. Estimates of EROI of coal and coal products production by year from various sources on a logarithmic plot[31].

[31] Estimates are arranged by the year of publication of the estimate where no other date was indicated by the author, hence they may not tally with dynamic estimates, see Appendix B for reference data.

Conventional oil

This study located 100 estimates of the EROI of conventional oil production, again divided into dynamic and static estimates. The estimates have been further categorised by the region of analysis – World, US, UK, etc. Looking first at the dynamic estimates (see Figure 6-4) a strong decline in the energy return is seen from the early twentieth century, from between 50-100, until the sixties where the value was around 20-30. Some authors show a peak in energy return sometime around 1970 and a rise around 1990, while others show simply a terminal decline.

Smil (2008, p.227) writes, “Energy invested during the 1930s and 1940s in the discovery of the largest Middle Eastern oilfields was extraordinarily low, on the order of 1MJ/t or 0.0025% of the hydrocarbons in place and the subsequent production cost from these huge reservoirs (≈ 0.5-5 GJ/t) yielded wellhead EROI as high as $10^3 - 10^4$.” Unfortunately, crude oil has an energy density of around 45 MJ/kg, which gives an EROI of 9 – 90, not 1000 – 10,000. The lower estimate has been used.

Turning to the static estimates, the majority of the estimates lie in the region between 10 and 100 with the overall trend being again downward, if only slightly. The data for the World stays in the region 15-30 except during the period 1974-1980, during which it dropped below 10. This may be a consequence of the oil shocks during this period. Estimates for the US seem to decrease from around 100 in the 1930s to the region between 10-30 from 1955-2010. The data for the UK is displays a large spread. Unsurprisingly, the data for estimates where the region is unspecified shows the largest spread. The mean value of all estimates is 22.

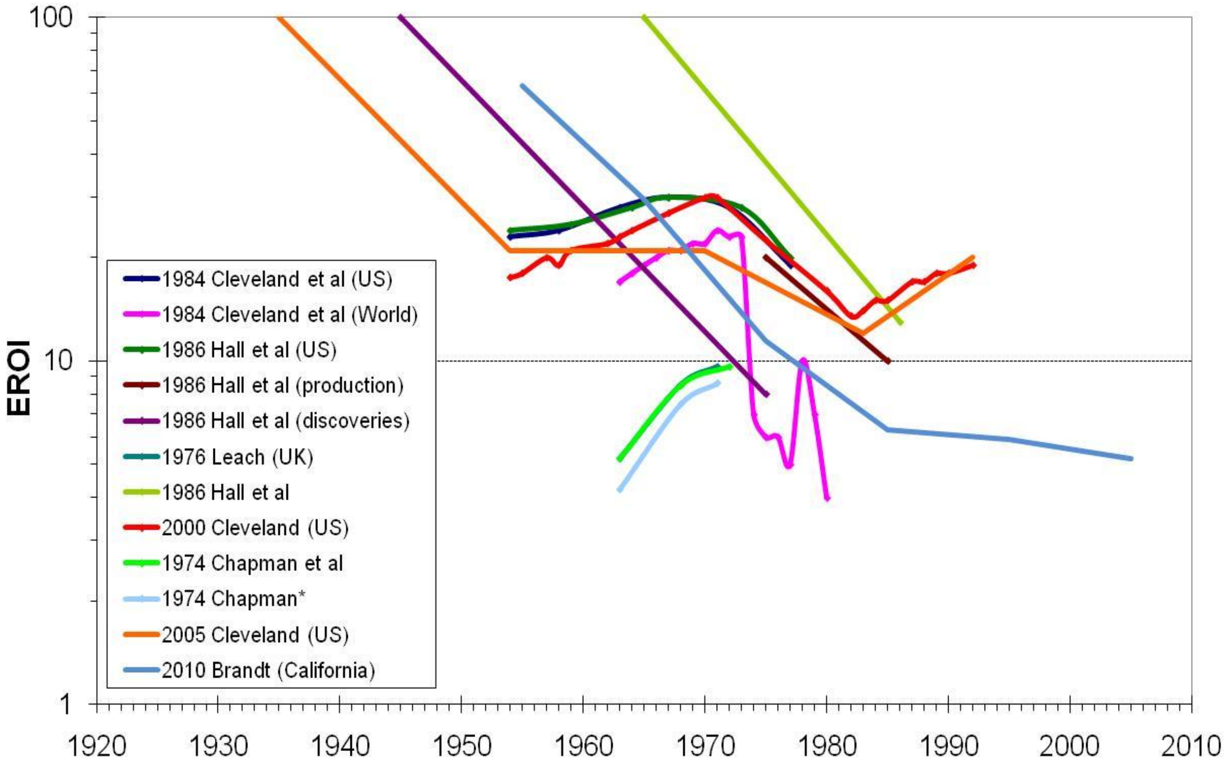


Figure 6-4. Dynamic estimates of EROI of conventional oil production.
Data taken from various sources: (Cleveland, et al., 1984), (Cleveland, 2005), (Charles A.S. Hall, et al., 1986), (Leach, 1976), (Zucchetto, 2004), (Hopkins, 2008), (Cleveland, et al., 2000), (P. F. Chapman, et al., 1974), * data from (Boustead & Hancock, 1979)

Figure 6-5. Estimates of EROI of conventional oil production by year from various sources on a logarithmic plot. Most of the estimates are below 100. There is a slight downward trend in the estimates over time.

Unconventional oil

Estimates of the energy return for unconventional sources of oil are few and far between, which is surprising given the hopes held out for them as a replacement for diminishing conventional oil production. This study located 5 estimates of the EROI for oil production from tar sands and 14 for shale oil. No estimates could be found specifically for the EROI of production of NGL, Polar, Deep Water or Heavy oils.

There was a spate of estimates in the late nineteen seventies around the time of the world oil shocks and then very little interest until after 2005, presumably in response to fears over the peak in conventional oil production (see Figure 6-6). As can be seen, the energy return is much lower for unconventional oil sources than for conventional sources, sitting somewhere in the region of 0 to 20 for oil shale and 0 to 10 for tar sands, with mean values of 9 and 4, respectively. Several of the estimates suggest an energy return below one (which represents the 'breakeven' point); meaning that the production process requires more energy than it ultimately produces.

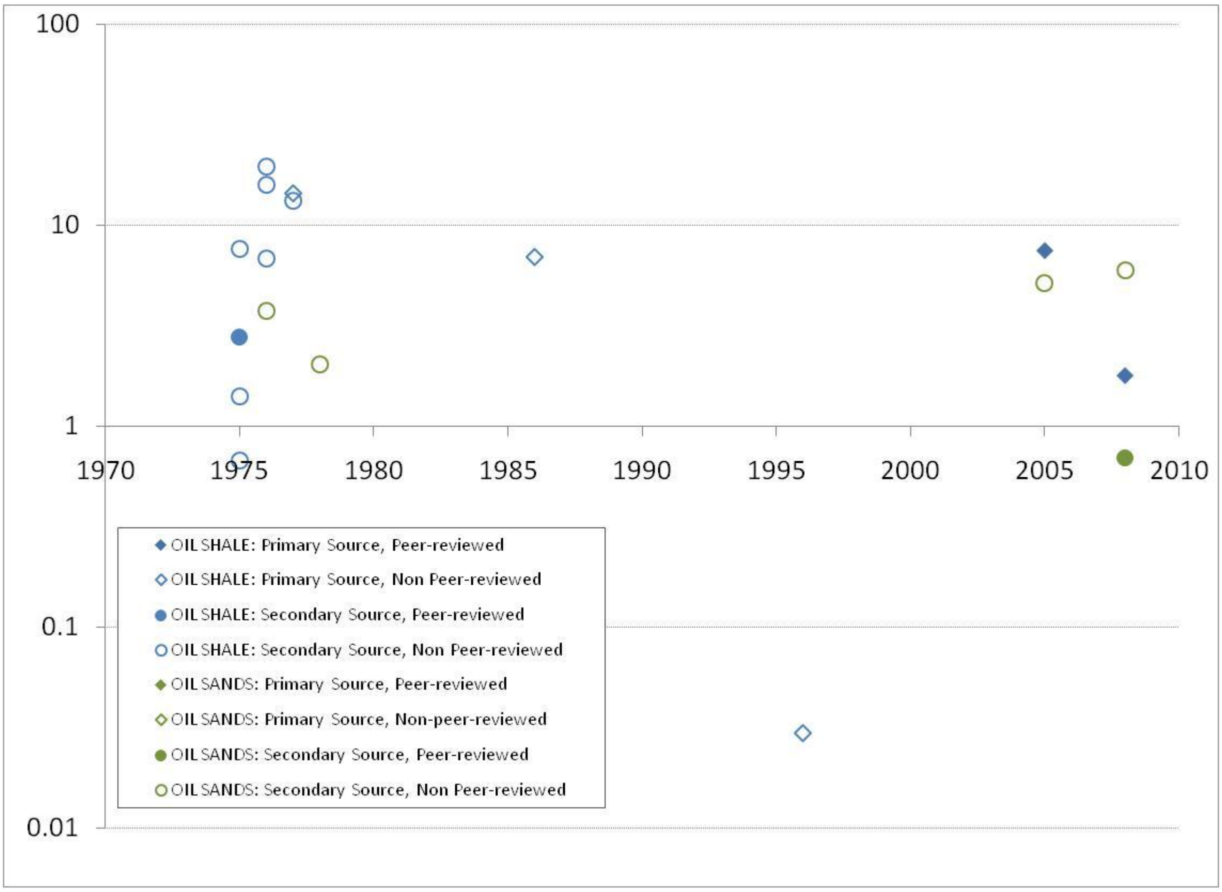


Figure 6-6. Estimates of EROI of unconventional oil production by year from oil shale and tar sands. The mean of estimates for oil shale, is higher than tar sands.

Conventional gas

There are few estimates for the energy return on gas production, far fewer than for either oil or coal. This study located 25 estimates for the EROI for conventional gas production categorised as dynamic estimates of gas production, static estimates and estimates of electricity production using natural gas.

Looking at the dynamic estimates, there is a convergence towards a value for the EROI of around 10, however, some from below and some from above (see Figure 6-8). Most of the estimates lie under a value of 20 for the energy return; however, one outlying estimate, from Voss (2001), puts the EROI of electricity generation from gas at around 300. Given that the range of values for EROI of gas production is 1.84 – 100, this seems unlikely.

There is little discernible trend in the static estimates. The mean of all estimates of gas production is 17 and the mean of estimates for electricity production is 49. This result is anomalous, since the EROI of electricity production should be lower than gas production due to losses during generation. The reason for the anomaly may be twofold: the low number of overall estimates and the outlying large estimate for electricity generation. Re-calculating the mean for electricity without the outlying estimate gives a value of 7.

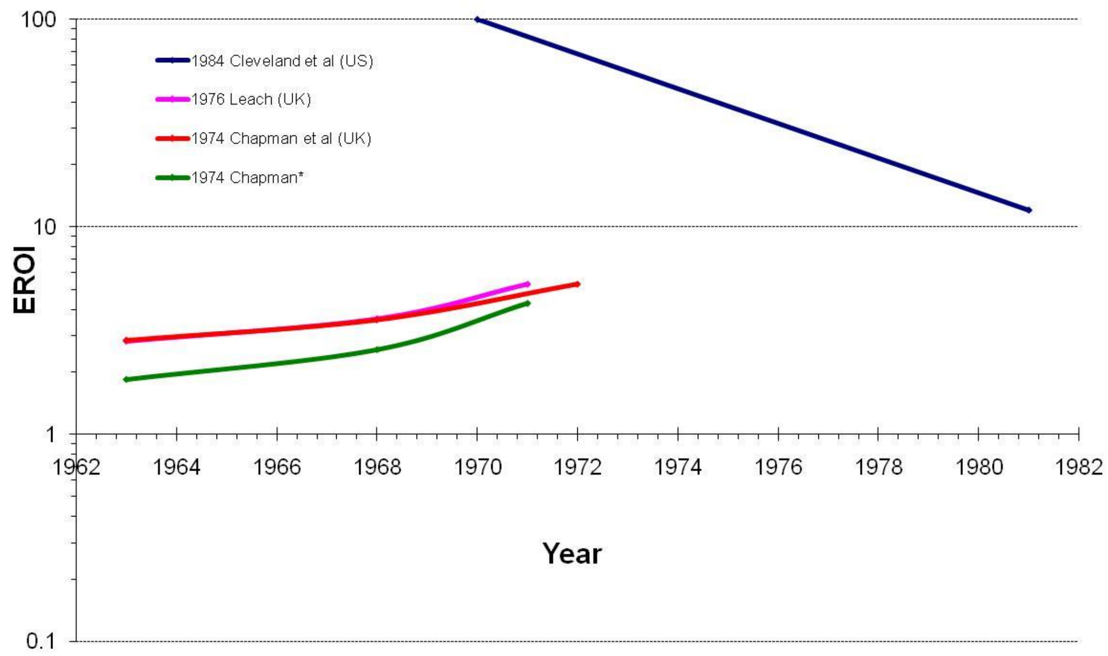


Figure 6-7 Dynamic estimates of EROI for conventional gas production from various sources on a logarithmic plot. Dynamic estimates show both increases and decreases over the same period, depending on the data source.

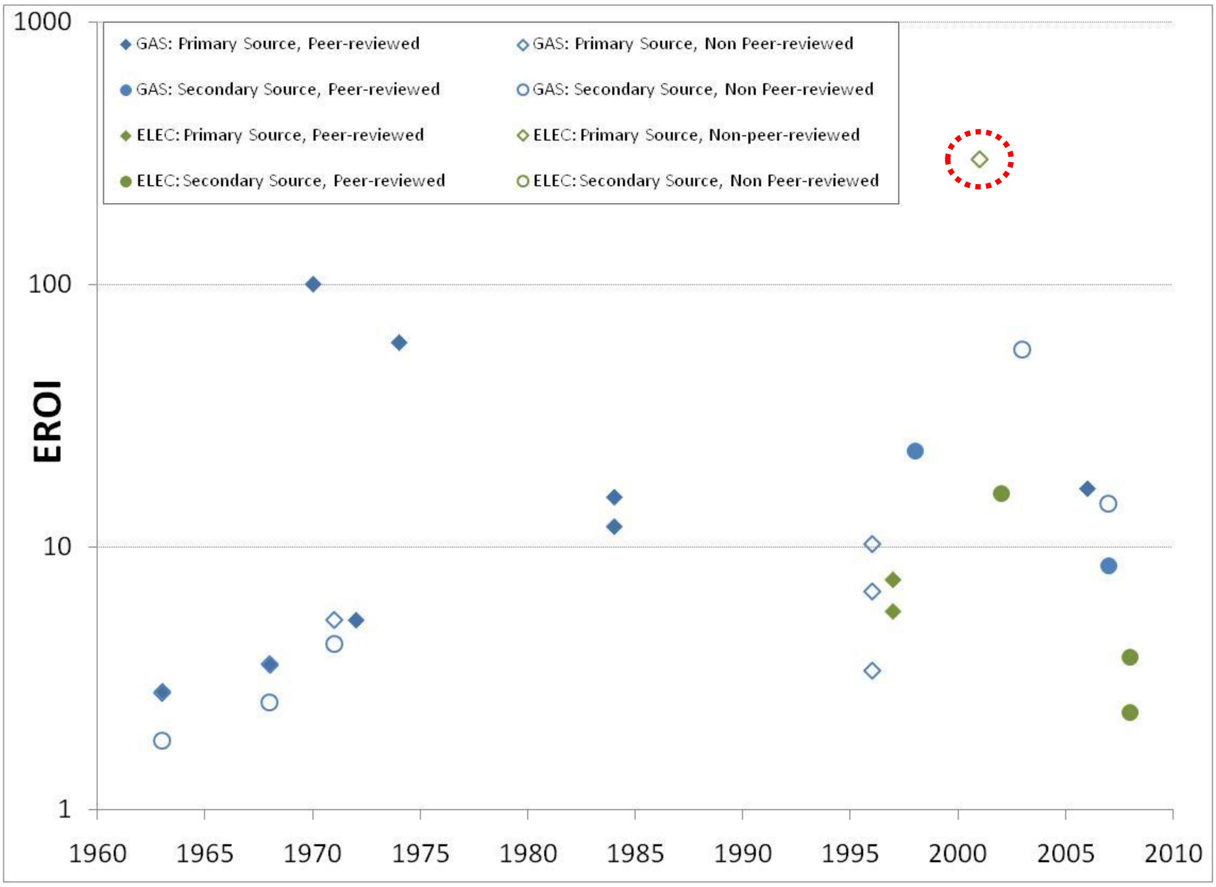


Figure 6-8. Estimates of EROI for conventional gas production from various sources on a logarithmic plot. There is little obvious trend in estimates over the time period for either gas or electricity production.

Unconventional gas

This study located only two estimates for the EROI for gas production from unconventional sources. Both of these estimates lie in the region between 1 and 6 with a mean of 3, so are low, but they do offer at least some positive return on energy invested.

Nuclear fission

This study located 36 estimates for the energy return for electricity generation from nuclear energy. There are two outlying data points, from Bullard (1978) and Voss (2001), whose values are nearly an order of magnitude greater than the rest. Again there is a reduction in the number of estimates between 1980 and 1995, otherwise there is little obvious trend in the estimates. The mean of all estimates is 21 when the outlying estimates are included and 9 if they are excluded.

Although many of these studies included energy requirements for de-commissioning of the nuclear plants, very few have included energy costs of long-term storage of waste products, which may be large. Hall et al. (1986) have estimated the negative change to EROI values of including various possible issues including decommissioning (1.2%), steam tube or embrittlement problems (1.6 to 1.8%) and clean-up after Three Mile Island-type incident (21%).

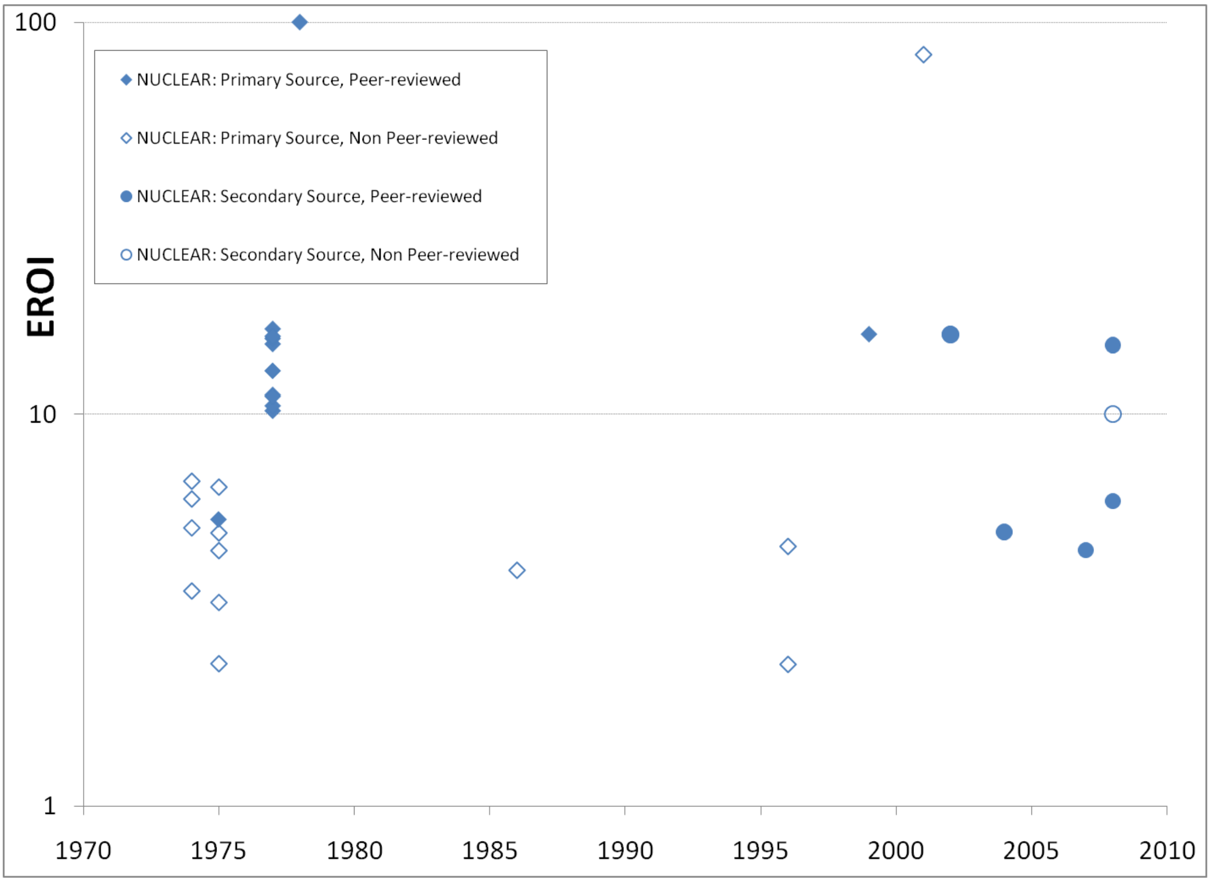


Figure 6-9. Estimates of EROI of energy production from nuclear fission by year from various sources. There is little obvious trend in the estimates over time. There are two outlying data points whose value is nearly an order of magnitude greater than the others.

6.1.2. Renewable energy sources

Biomass

Since the late nineteen nineties, there has been a great deal of interest in biological sources of energy, especially as a liquid fuel to offset future declining oil production. This interest is reflected in the ubiquity of estimates of energy returns for biomass production, which have been classified under four categories: solid biomass, bio-ethanol, bio-diesel and electricity production from biomass (including co-firing with coal).

This study located a total of 190 estimates; 48 for solid biomass, 72 for ethanol, 28 for bio-diesel and 42 for electricity production. The mean values of all estimates are 20 for solid biomass, 5 for bio-ethanol, 2 for bio-diesel and 13 for electricity[32]. Looking at the data, it can be seen that the energy returns for ethanol and diesel production are generally lower than for electricity production (see Figure 6-10). Many of the bio-diesel production processes (and some of the ethanol production processes) have an energy return of less than one, meaning that the energy inputs into the process (not including the energy content of the biomass) is less than the energy content of the final product. Many of the biomass production processes have an EROI of between 10 and 100, offering energy returns comparable with present day fossil fuel production.

[32] This result seems slightly odd since it would be expected that, given enough sample data, the relative EROI of solid biomass and electricity production should at least reflect the efficiency of electricity production of around 30%. A number of explanations are possible. Firstly, that the EROI values have been ‘quality corrected’ to reflect the higher quality of electricity as an energy carrier over that of biomass. Secondly, that electricity production utilises only those resources which are known to have higher returns, whereas the solid biomass estimates reflect more of a trial and error procedure of testing processes with varying degrees of energy return. Otherwise, this may simply reflect the uncertainty within the data.

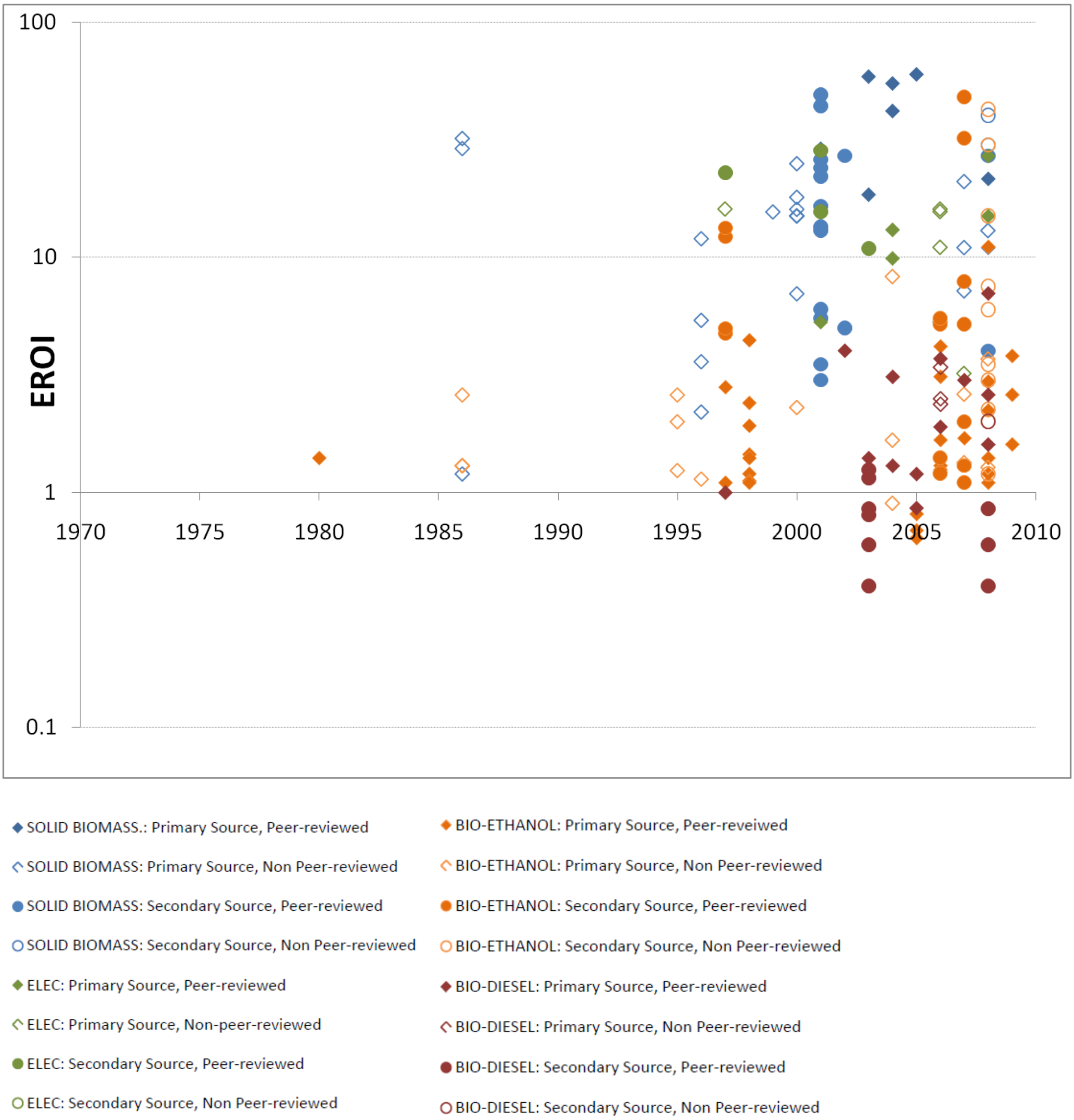


Figure 6-10. Estimates of EROI for all biomass energy production by year from various sources.
There has been an explosion of interest in biomass as an energy source reflected in the huge increase in estimates of energy returns since 1995. There is no obvious trend in the estimates over time.

Hydro

This study located 16 estimates for the EROI for hydro energy production, some of which are for run-of-river systems, with the majority for dam and reservoir systems. There is a large discrepancy in the estimates, mainly due to the specificity of each location (or potential location). Many of the estimates are over 100 and there is an upward trend in the estimates over time (see Figure 6-11), perhaps reflecting the existence of dams that are still generating long after their expected lifetime, such as the Arapuni hydro station on the Waikato River, which has been operating since 1929 (Mighty River Power, 2007) or cases where generating capacity has been retro-fitted to existing dams originally built for other purposes, thus saving on construction costs (Sims, 2008). The mean of all estimates is 84.

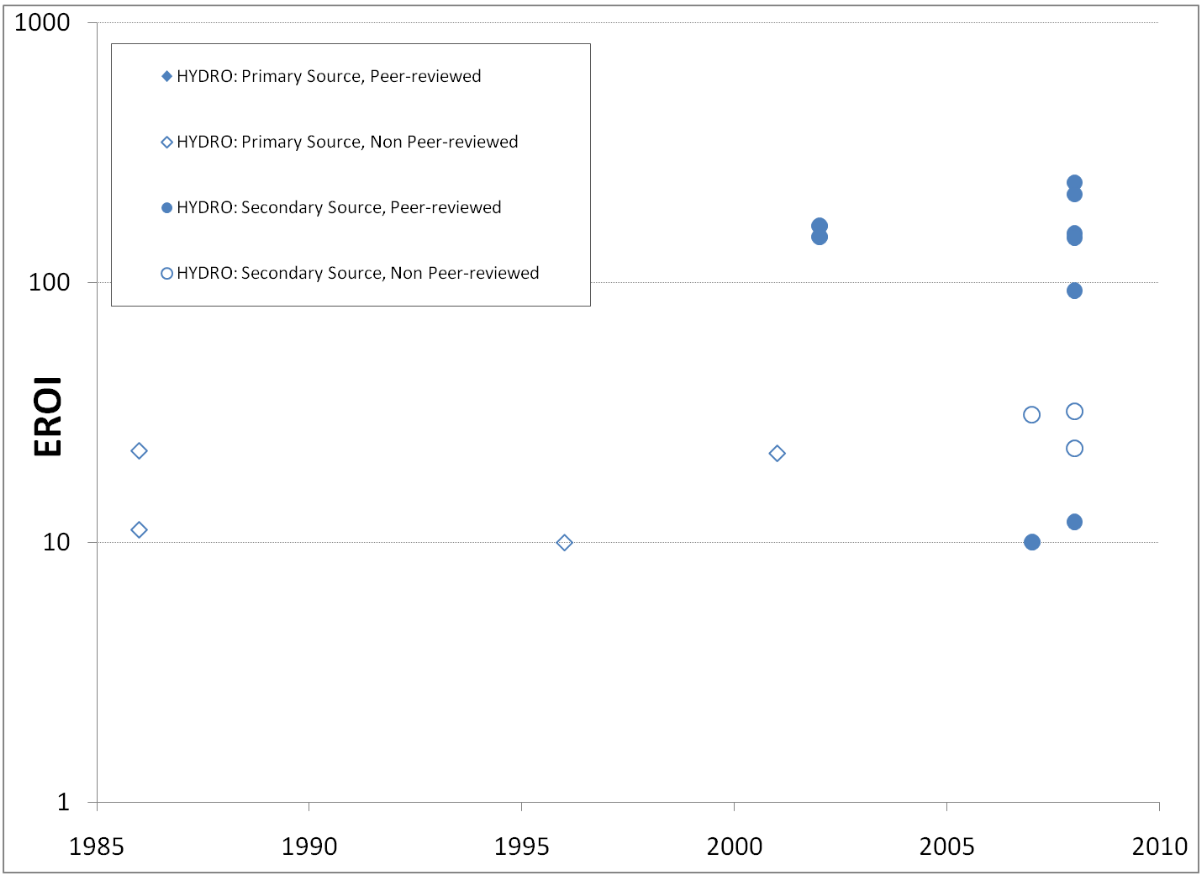


Figure 6-11. Estimates of EROI of hydro energy production by year from various sources. There is an upward trend in the estimates over time. The mean value of all estimates is 84

Geothermal

This study located 29 estimates of the EROI of geothermal energy generation. The estimates all fall between 1 and 25 (see Figure 6-12). There is a convergent trend in the estimates over time toward a value of around 10; however, this may just be a consequence of lack of data since the nineteen eighties. The mean of all estimates is just under 10.

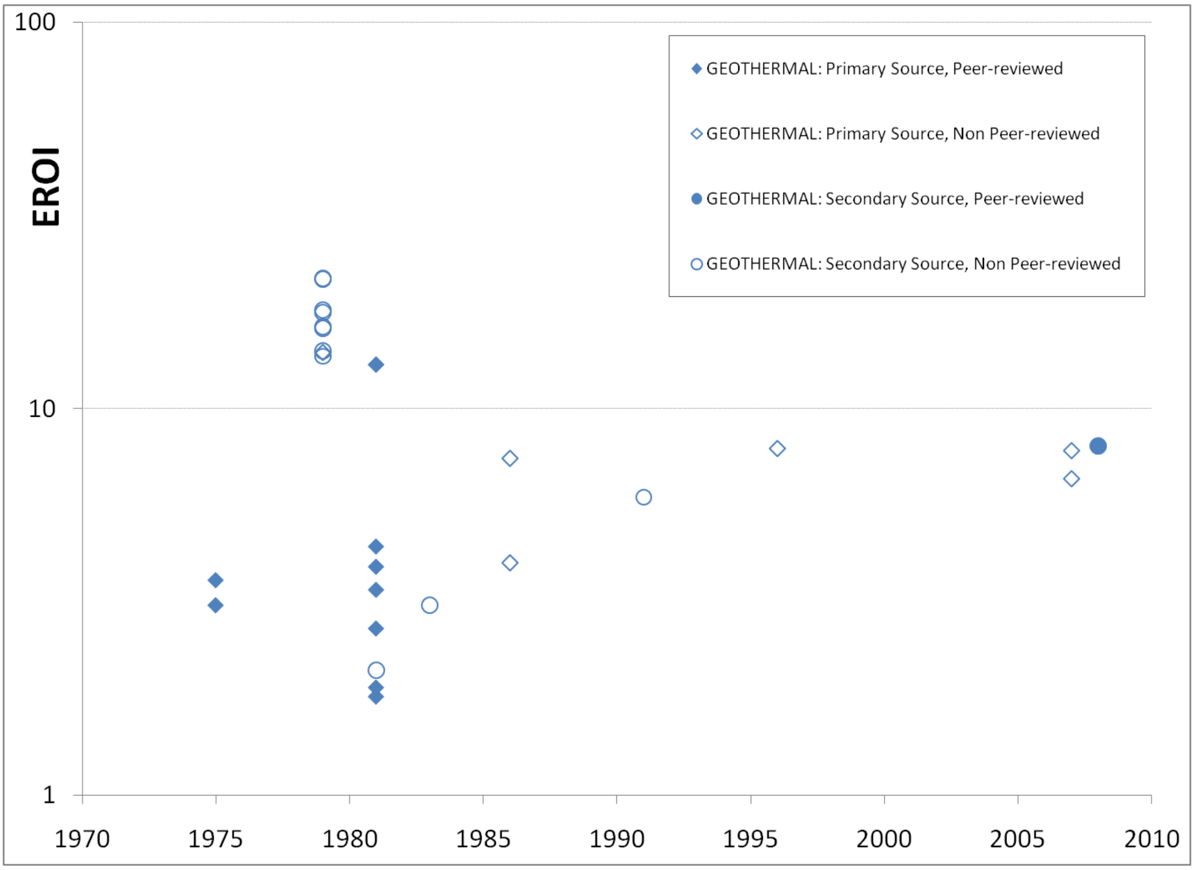


Figure 6-12. Estimates of EROI of geothermal energy production by year from various sources.
All estimates lie between 1 and 25 with a convergent trend over time to a value of around 10. The mean of all estimates is just under 10.

Wind

This study located 28 estimates for the EROI for wind energy production, however, some of these data 'points' themselves actually represent meta-analyses of different studies, such as Kubiszewski and Cleveland (2008), who analysed 119 turbines in 50 different studies. They found the mean of all turbines operational at the time of analysis to be 20. Two of the low-lying estimates, from Allen et al. (2008), are for 'micro' wind turbines in an urban setting. The range of estimates is 42 (see Figure 6-13). The mean of estimates is 24.

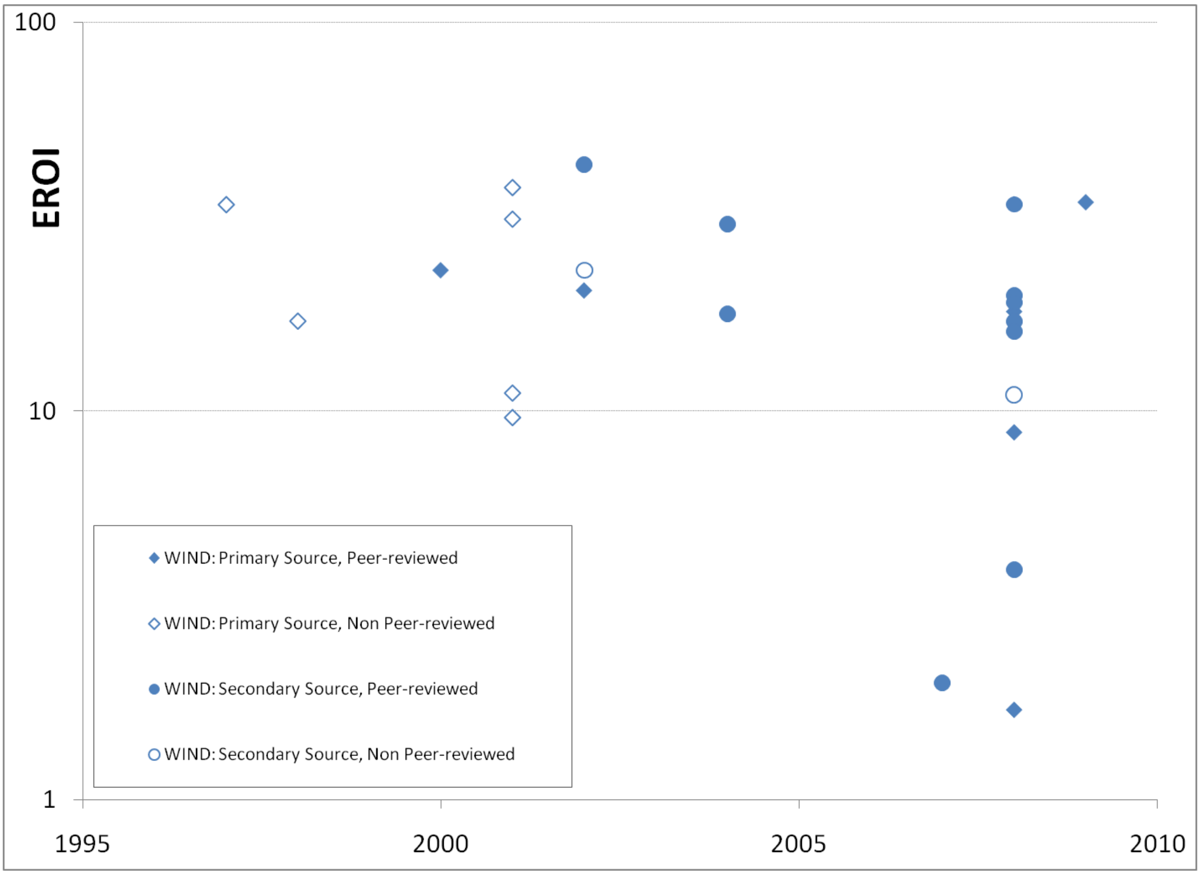


Figure 6-13. Estimates of EROI of wind energy production by year from various sources

Solar

The solar resource is divided into three separate categories: solar thermal, photovoltaics (PV) and solar thermal energy conversion (STEC) using concentrating plates (either parabolic dish, trough or onto a central tower). This study located 10 estimates for solar thermal systems, 42 for PV systems and 2 for STEC systems with means of all estimates being 5 for PV, 6 for solar thermal and 11 for STEC. There has been a marked increase in analysis of solar systems since 2000 and a corresponding increase in EROI over time; possibly reflecting improvements in technology over the period (see Figure 6-14). Three of the estimates for PV are below an EROI of one, meaning that the process consumes more energy than it delivers. The greatest estimate for PV is 74.6 (Mason, Fthenakis, Hansen, & Kim, 2006). The very high EROI for some PV data is perhaps surprising, despite technology improvements

Figure 6-14. Estimates of EROI of all solar energy production by year from various sources. There has been a significant increase in studies since 2000, with an upward trend in estimate values over time.

All ocean

The ocean resource is comprised of three separate sources of energy: tidal energy caused by the gravitational interaction of the Sun, Earth and Moon, which can be harnessed by barrages, lagoons or the tidal stream method (resembling underwater wind turbines); wave energy caused by the interaction of the wind across open water, harnessed by a variety of methods; and ocean thermal energy conversion (OTEC) utilising the thermal gradient between the ocean surface and cooler, deeper waters to drive a low temperature cycle engine.

This study located three estimates of the EROI for tidal energy, two for wave energy and four for OTEC energy systems. The estimates (see Figure 6-15) show that the energy returns for OTEC systems are much lower, with a mean of 4, than both tidal, mean of 40, and wave energy systems, mean of 18. This reflects the large infrastructural requirements and low efficiency, symptomatic of low temperature thermodynamic systems. Tidal systems are estimated to have large energy returns and have the benefit of being a perfectly predictable energy source (not suffering the variability and intermittency of other renewable sources) but they have the disadvantage of only being applicable in a few sites worldwide. Wave energy has a good return and there are many potential sites globally, but suffers from difficulties of maintenance and being a very diffuse source of energy.

Figure 6-15. Estimates of EROI for all ocean energy production by year from various sources.
There is a downward trend in estimates for OTEC (green) over time and estimates of Tidal (blue) seem to increase over time; however the sample size is small for all three energy sources.

6.1.3. Summary

The results from the literature review on energy-return-on-investment (EROI) of all energy sources is summarised in Figure 6-16 and Table 6-2. There is a large range in the EROI data, in most cases over one order of magnitude and in some cases over two orders of magnitude. In the majority of cases the median is less than the mean, indicating a skew in the distribution of the estimates. The majority of energy sources offer an EROI of less than 20. In general, renewable energy sources do offer lower EROI than non-renewable sources. Notable exceptions to this rule are hydro (which has a highly skewed distribution) and tidal (for which there are only 3 estimates). However, when secondary energy products, such as electricity, are compared, then renewable sources, in the form of hydro, tidal, and wind, offer three of the four best energy returns.

Such an analysis suggests that renewable sources may contend with non-renewable sources as a supplier of electricity. The energy-return-on-investment perspective only offers one possible comparison; in order to further enable evaluation of renewable and non-renewable resources, other contrasting features of the two types of resource need to be compared.

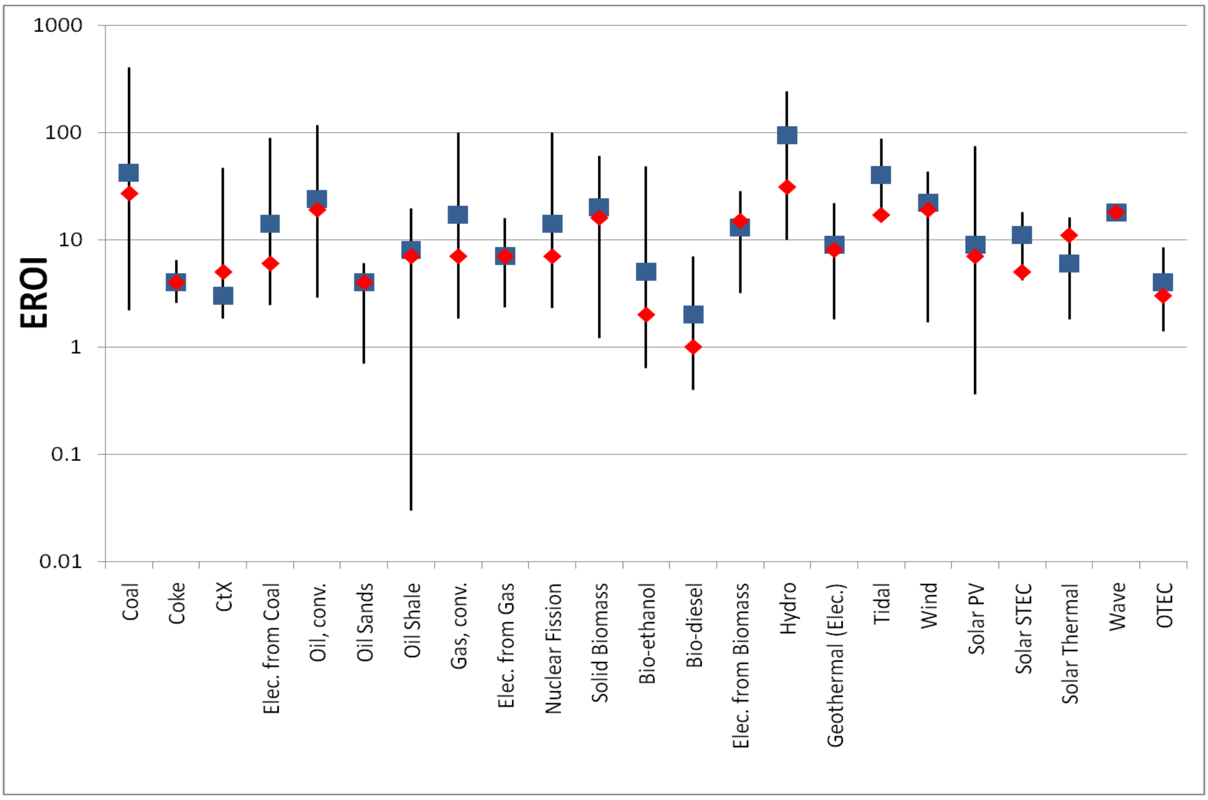


Figure 6-16. EROI of all energy sources.
Squares represent mean (blue) and median (red) of all estimates, vertical lines represent the range of EROI estimates. The majority of energy sources offer an EROI of less than 20.

Table 6-2 Summary of EROI data for all energy sources

Energy Source	Number of estimates	Range (max – min)	Mean	Median
Coal products				
Coal	76	399	42	27
Coke	7	4	4	4
Electricity	18	87	14	5
Gas	8	5	3	6
Conventional Oil	116	114	24	19
Unconventional Oil				
Oil sands	5	5	4	4
Oil shale	15	20	8	7
Conventional Gas:				
Gas	21	98	17	7
Electricity	9	298	49	7
Electricity (excluding outlier)	8	14	7	6
Unconventional Gas	-	-	-	
Nuclear Fission	33	98	14	7
Nuclear Fission (excluding outliers)	31	14	9	7
Biomass products:				
Solid biomass	48	59	20	16
Bio-ethanol	73	47	5	2
Bio-diesel	28	7	2	1
Electricity	14	24	13	15
Hydro	16	257	94	31
Geothermal:				
Electricity	29	20	9	8
Tidal	3	72	40	17
Wind	28	41	22	19
Solar:				
PV	42	74	9	7
Thermal	10	15	6	5
STEC	2	14	11	11
Wave	2	5	18	18
OTEC	4	7	4	3

6.2. Capital intensity of renewable energy production

Energy-return-on-investment values allow the determination of the total energy subsidy received by an energy process. Looking at the capital intensity of that energy source allows an investigation on how that subsidy is proportioned between process energy and energy embodied in the form of capital.

This investigation has two main purposes. Firstly, the information gained will provide evidence to support assumption 7 of the main argument of the thesis, that “renewable energy sources are more capital intensive than non-renewable energy sources.” Secondly, this information is necessary in order to estimate the value of the parameter CAPITAL FACTOR, used in the GEMBA model to relate the variable ANNUAL ENERGY PRODUCTION with the variable ENERGY SECTOR CAPITAL STOCK.

The analysis within this section firstly looks at some of the reasons for the differences between renewable and non-renewable energy sources and how these affect the capital intensity of each, before turning to estimates of the ratio of capital inputs to total energy inputs of energy production processes.

6.2.1. Dilute nature of renewable energy flows

Renewable energy sources tend to be diffuse by nature, for example, compare the power density of air flowing through a wind turbine with the energy flow through an oil pipeline. The maximum possible energy extraction from a body of air with density ρ, moving at velocity ν, is defined by the Betz-Lancaster Limit as:

$$P_{\max} = \frac{16}{27}\frac{1}{2}\rho_{air}Av^3$$

Since the density of air is around 1.225 kg/m^3 (Patel, 2006) and wind turbines are normally rated at a wind speed of around 10 m/s (Ackermann, 2005), the maximum possible power density of a wind turbine is somewhere of the order of 1000 W/m^2.

Imagine now oil flowing at a rate of 10 litres per second through a pipeline of diameter 0.2m which has a cross-sectional area of 0.126m^2. Since the energy content of crude oil is 38.7 MJ/l (IOR, 2005), the energy content of 10 litres of crude oil is approximately 387 MJ. A flow rate of 387 MJ every second thus equates to a power density of around 3000 MW/m^2, or somewhere in the order of 10^9 W/m^2.

Figure 6-17 shows the approximate power density and typical areas of a number of energy producers and consumers. The power densities of the fossil fuels coal and oil, as represented by the state in which they are found in nature – oil fields and coal seams – are much higher than those of the renewable energy sources, e.g. river valleys for hydro schemes or geothermal ‘hot spots’.

If such low power density sources are to generate energy on the scales demanded by modern society, then the infrastructure required to harness those flows must increase inversely to the power density – the more diffuse the sources, the larger the infrastructure needed.

The reason for the large concentration of energy represented by fossil fuels is due to their, literally, being *concentrated* forms of vast flows of solar energy; flows concentrated both over time and through time. The energy contained in a litre of petroleum may well represent millions of years’ worth of accumulation of sunlight which has been stored over time and then been further concentrated through time by compression and heat from geological activity. The work to transform the biomass into a useful fuel has been done for us, although over a time frame of millions of years. This should be compared with present day processes of bio-fuel production, in which society must supply the energy necessary for production.

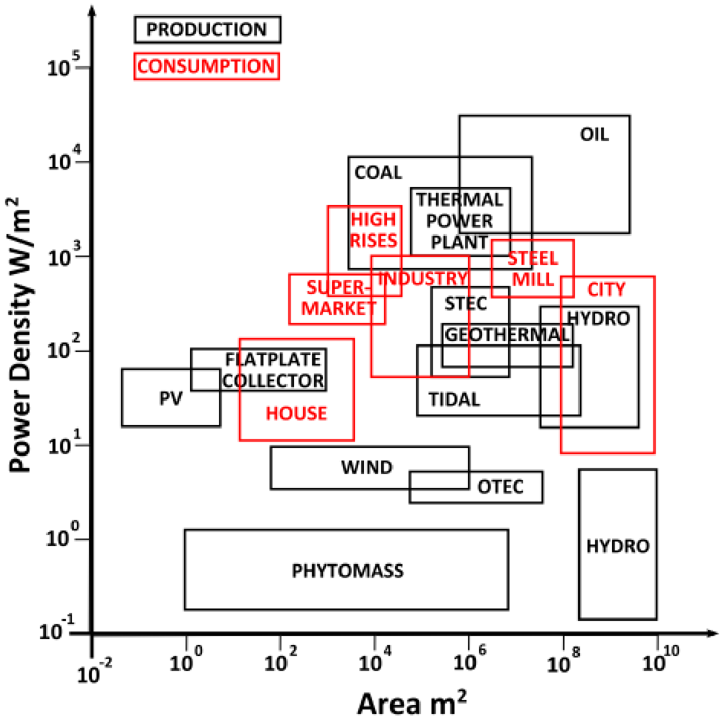


Figure 6-17. Power density and area of various producers and consumers of energy on a log-log plot, adapted from (Vaclav Smil, 2003).
Renewable energy sources have much lower power densities of. Many consumers of energy in modern day society have ‘evolved’ to take advantage of available high power densities offered by fossil fuels.

6.2.2. Energy inputs into energy production process

Any production process requires the input of energy both in the form of process energy, such as electricity or heat, and inputs of energy embodied in the form of physical capital. Consider the case of a transport service delivered by a private vehicle as depicted in Figure 6-18. Direct energy inputs, displayed in bold, include only the energy needed to deliver the operating fuel for the vehicle. Expanding the boundary of the analysis encompasses capital inputs required for fuel delivery, such as pipeline and filling station construction, as well as energy and capital inputs for car manufacture, but this may well be expanded to include inputs required for such purposes as road construction.

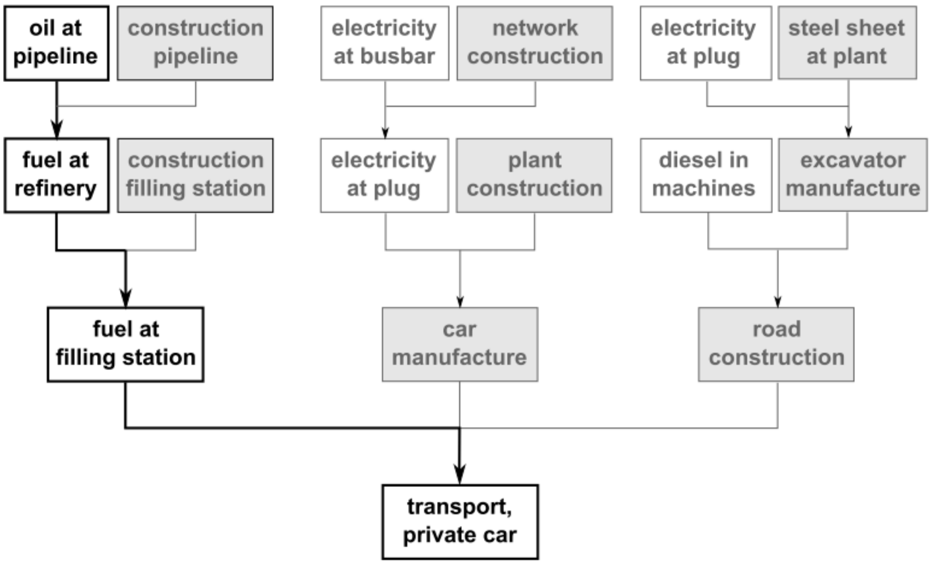


Figure 6-18. Flow chart of a simplified system of transport service from a private car, from (Frischknecht et al., 2007, p. 3).
Often only direct energy inputs in bold are considered during energy analysis. Analysis may be extended to include both energy (white boxes) and capital inputs (grey boxes) of both direct and indirect processes, such as vehicle manufacture or construction of necessary infrastructure.

In general, most energy analysts either do not include, or do not distinguish, capital and process energy inputs during their analysis, as this quote from Boustead and Hancock illustrates:

> "Because of the difficulties encountered with the estimation of capital energy, many workers [in energy analysis] adopt a third strategy and omit this element completely from their calculations. Capital plant depreciation, in energy terms, for the U.S. coal-mining industry is about 5% of the total production energy or about 0.25% of the total fuel energy (that is fuel energy content plus production energy). The omission of capital energy in this instance would therefore introduce only a very small error" (Boustead & Hancock, 1979, p. 120)

As stated, the justification for ignoring the contribution of capital inputs is small in the case of coal production and in the case of "generation of electricity it [capital energy] was only about 0.4% of the total system energy requirement." (Boustead & Hancock, 1979, p. 178). The authors do, however offer a caveat to this general rule of thumb.

> "Although capital energy is usually a relatively small contributor to total system energy requirement, this is not always so. In situations where machines operate under particularly arduous and demanding conditions, the lifetime of the machines or parts of the machines may be very short indeed." (Boustead & Hancock, 1979, p. 180)

A number of recent studies have been conducted on capital inputs into the energy production process. Dones and Frischknecht (1998), in their analysis of mono- and polycrystalline silicon cell photovoltaic panels, assume that around 1% of the GHG emissions (which shall be used as a proxy for energy consumption) result from installation, with no discussion of maintenance. Decommissioning is considered in terms of material waste flows only.

Hondo (2005) makes a life-cycle analysis of electricity generation options for Japan. For coal, 90% of the GHG emissions are associated with the combustion of the fuel. Of the remaining 10%, 3.3% comes from operation (of which 2.6% is mining and transporting the fuel). Only 0.4% comes from construction of the plant. The results for oil powered plants are much the same: 94.9% from fuel combustion; 4.7% from operation (of which 3.9% is for extraction, processing and transport); and only 0.3% from plant construction. The results for LNG are slightly different, with nearly 20% coming from operation; however plant construction still only accounts for 0.5%. In the case of nuclear energy, plant construction accounts for over 10% of the emissions and a further 4.7% comes from decommissioning and spent fuel storage. Turning to renewable energy, a very different picture is seen. In the case of hydropower, the split between construction and operation is 82.8% and 17.2% respectively. For geothermal, construction accounts for 35.3% of emissions and operation for 64.7% (however 30% of this 'operation' is for "exchange of equipment" and so may well include capital costs). The results for wind power have a 70:30 split between construction and operation, and PV has a 77:23 split.

Swedish group Vattenfall (1999), in their assessment of electricity generation, found that for hydropower, around 20% of CO_2 emissions come from plant construction and 75% from "construction, operation and demolition" of the distribution network. For wind power, construction contributes around 55% and the network contributes around 40%. In the case of nuclear, construction contributes around 5% and the network around 40%.

Meier (2002) found that around 1% of the energy flow through a natural gas power plant is due to construction and decommission, around 4% is in operation and the remaining 95% is due to the fuel cycle (this figure does not include the energy content of the fuel but only the energy used in bringing the fuel to the plant). For PV, 95% of the energy flow is associated with construction and decommissioning, the balance being used in operation and maintenance.

Frischknecht et al. (2007) investigated the impact of capital requirements on life cycle assessments for various goods and services. Their results, for the proportion (10%-median-90%) of cumulative (fossil fuel) energy demand that is taken by capital requirements in various electricity supply chains, are:

- hard coal (0.8% - 1.2% - 1.8%);
- lignite (0.3% - 0.3% - 0.3%);
- oil (2.2% - 2.2% - 2.2%);
- natural gas (standard power plant) (0.6% - 0.8% - 1.0%);
- natural gas combined cycle (best technology) (0.9% - 0.9% - 0.9%);
- cogeneration using natural gas (1.2% - 1.4% - 1.6%);
- cogeneration using diesel (2.6% - 2.6% - 2.6%);
- nuclear (23.3% - 31.8% - 37.7%);
- cogeneration using wood (27.3% - 30.5% - 33.9%);
- wind (97.6% - 97.7% - 98.5%);
- photovoltaic (100.0% - 100.0% - 100.0%) and;
- hydro-electric (98.4% - 98.4% - 98.6%).

6.2.3. Summary

The studies made on the capital intensity of energy production are summarised in Table 6-3. They show a large disparity between renewable and non-renewable energy sources, offering strong support for the assumption that "renewable energy production is more energy intensive than non-renewable". Assuming that greenhouse gas emissions are a suitable proxy for energy consumption; in general, capital inputs into energy production from fossil fuels tend to be below 5% of their total energy inputs, but for nuclear this figure is around 30% and for hydro, wind and PV it is at least 95%.

The implications of the greater capital intensity of renewable energy sources are explored using the GEMBA model.

Table 6-3. Capital requirements into energy production process from various authors

Author	*Energy Source*	*Proportion of investment for capital*
(Dones & Frischknecht, 1998)	PV	1% GHG emissions from installation
(Hondo, 2005)	Electricity from coal	0.4% GHG emissions from plant construction
(Hondo, 2005)	Electricity from oil	0.3% GHG emissions from plant construction
(Hondo, 2005)	Electricity from LNG	0.5% GHG emissions from plant construction
(Hondo, 2005)	Nuclear	Around 15% GHG emissions from construction, decommissioning and spent fuel storage
(Hondo, 2005)	Hydro	82.8% GHG emissions from plant construction
(Hondo, 2005)	Geothermal	35.3% GHG emissions from plant construction, 30% from "exchange of equipment"
(Hondo, 2005)	Wind	70% GHG emissions from construction
(Hondo, 2005)	PV	77% GHG emissions from construction
(Vattenfall, 1999)	Hydro	20% CO_2 emissions from plant construction, 75% from "construction, operation and demolition" of the distribution network
(Vattenfall, 1999)	Wind	55% GHG emissions from plant construction, 40% associated with network.

Author	Energy Source	Proportion of investment for capital
(Vattenfall, 1999)	Nuclear	5% GHG emissions from plant construction, 40% associated with network
(P. J. Meier, 2002)	Electricity from gas	1% of energy due to plant construction
(P. J. Meier, 2002)	PV	95% of energy due to construction
(Frischknecht, et al., 2007)	Hard coal	0.8-1.8% of energy for capital requirements
(Frischknecht, et al., 2007)	Lignite	0.3% of energy for capital requirements
(Frischknecht, et al., 2007)	Oil	2.2% of energy for capital requirements
(Frischknecht, et al., 2007)	Electricity from gas (standard)	0.6-1.0% of energy for capital requirements
(Frischknecht, et al., 2007)	Electricity from gas (NGCC)	0.9% of energy for capital requirements
(Frischknecht, et al., 2007)	Electricity from gas (co-gen)	1.2-1.6% of energy for capital requirements
(Frischknecht, et al., 2007)	Electricity from diesel (co-gen)	2.6% of energy for capital requirements
(Frischknecht, et al., 2007)	Nuclear	23.3-37.7% of energy for capital requirements
(Frischknecht, et al., 2007)	Electricity from wood (co-gen)	27.3-33.9% of energy for capital requirements
(Frischknecht, et al., 2007)	Wind	97.6-98.5% of energy for capital requirements
(Frischknecht, et al., 2007)	PV	100% of energy for capital requirements
(Frischknecht, et al., 2007)	Hydro	98.4-98.6% of energy for capital requirements

6.3. Meta-analysis of energy resource estimates

> "The emphasis on augmenting supply rather than on diminishing demand and the persistent belief that the development of resources always will yield an excess of social benefits over social costs have a great influence on the management of common resources, indeed on the very perception of a common resource" (E. F. Cook, 1976, p. 357)

This section offers the findings of literature reviews of estimates of *ultimately recoverable resources* (URR) of non-renewable energy sources (coal, conventional and unconventional oil, conventional and unconventional gas and uranium for nuclear fission) and of estimates of *technical potentials* of renewable energy sources (biomass, hydro, geothermal, tidal, wind, solar, wave and OTEC). The aim of this literature review is not as an in-depth analysis of the various estimates produced by different researchers, or to investigate the difference in assumptions that lead to the discrepancy in estimates between resource optimists, for example the USGS on the one hand, and resource pessimists, such as Colin Campbell, on the other. The results, instead, serve as a 'reality check' for the GEMBA model parameters ultimately recoverable resources and technical potential, when adjusted for the purposes of calibration and sensitivity testing. The data from the literature reviews is listed in Appendix C, along with more detailed analyses.

As can be seen from the summary diagrams in Figure 6-42 and Figure 6-43, there is a large range in the estimates of many of the energy sources, even those that have been utilised for a long time. This range is reflected in the wide range of modelling in CHAPTER 8.

6.3.1. Non-renewable energy sources

Over the years a great many studies have assessed and estimated the global endowment of fossil fuels as well as other resources, such as iron or other economically useful materials. These studies encompass a great many methodologies, some building up a global picture from the 'bottom up' on a field by field basis, others, such as the linearisation technique (as discussed in Section 3.1.1) or data on exploration, so-called "creaming curves"[33] (Laherrere, 2001), offer a 'top down' overview of a particular region, or even the global resource.

Classification of resources

[33] Creaming curves are a plot of cumulative discoveries as a function of cumulative exploration wells or distance drilled. Since exploration tends to display diminishing returns, such curves tend to asymptotically approach a limit which represents the ultimately recoverable resource.

Resources are classified according to the USGS/USBM system (M. Grenon, 1979), whereby a distinction is drawn between those resources that have been indentified and those still to be discovered and between those that are economic, i.e. able to be produced with current technology at or below the current market price, and those that are sub-economic. Hence the size of reserves will change with technological innovation and fluctuations in the market price of a commodity.

Several terms are utilised in order to make these distinctions clear (J. Edmonds & Reilly, 1985):

- ***Resource base*** – the broadest definition of the amount existing of a mineral; includes produced, unproduced, discovered and undiscovered amounts. The term carries no connotation of being producible under any reasonable set of costs or technologies.
- ***Recoverable resources*** – that part of the resource base, including discovered, undiscovered, produced and unproduced amounts, that is producible under a specified set of costs and technologies.
- ***Reserves*** – resources that are known to exist and are remaining in the ground at a specified date. Reserve figures include only those amounts of resources that are producible with technologies at the specified date at total costs not exceeding the market price at that date.
- ***Produced*** – resources that have been extracted by a specified date and have been consumed or stockpiled.
- ***Remaining resources*** – resources not produced by a specified date.
- ***Undiscovered resources*** – resources that have not been produced by a specified date and are not classified as reserves on that date.

In the following sections, a review of those studies that have produced estimates of ***ultimately recoverable resources*** (URR) for each of the fossil and fissile fuels is offered, in an attempt to discern any trends that may be used to determine a suitable range for the value of the parameter ULTIMATELY RECOVERABLE RESOURCES within the GEMBA model.

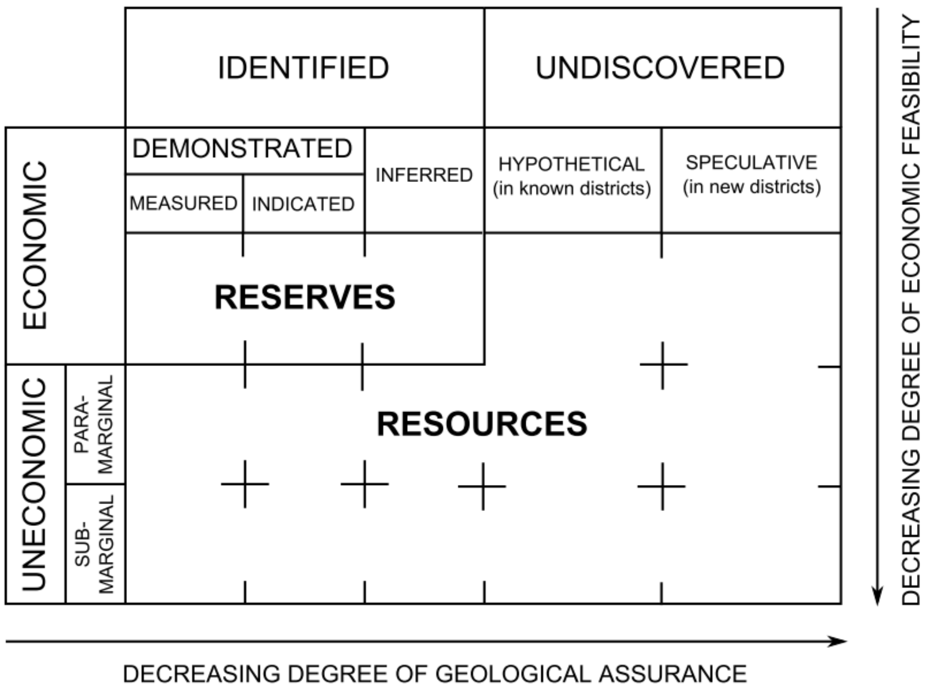


Figure 6-19. USGS/USBM classification of reserves and resources from (M. Grenon, 1979).
This depiction is known also as a McKelvey diagram, after the ninth director of the USGS, Vincent E. McKelvey. [34]

[34] From a biophysical perspective, there is some limit to those resources that might ever be considered 'economic', represented by an energy-return-on-investment (EROI) ratio of 1. Within purely monetary assessments there is no such limit. All resources may some day become 'economic' providing the market price of the commodity is higher than the cost of production.

Coal

A total of forty estimates were located from a variety of sources. Coals of differing quality, bituminous, sub-bituminous and lignite, were combined using the values 34, 30 and 27 MJ/kg respectively (Higman & van der Burgt, 2008). The earliest of these estimates dates from 1913 and the latest from 2008, with the majority being produced in the period 1977-1986, possibly in response to the oil shocks of the late seventies (see Figure 6-20). Most of the estimates (~80%) place the ultimately recoverable resources at under 50,000 EJ, whilst the full range is nearly five times this value. There is slight upward trend in the estimates over the time period.

The estimates have a mean of 40,800 EJ, a mode of 17,600 EJ and a median of 24,100 EJ (see Table 6-4). Assuming a normal distribution for these estimates gives a standard deviation of 44,900 EJ and a standard error of ~8000 EJ.

From the cumulative frequency of the estimates (see Figure 6-21) however, it can be seen that the distribution is far from normal, with the three quartile (25-50-75%) values of URR being 18,691 – 24,142 – 33,398 EJ respectively.

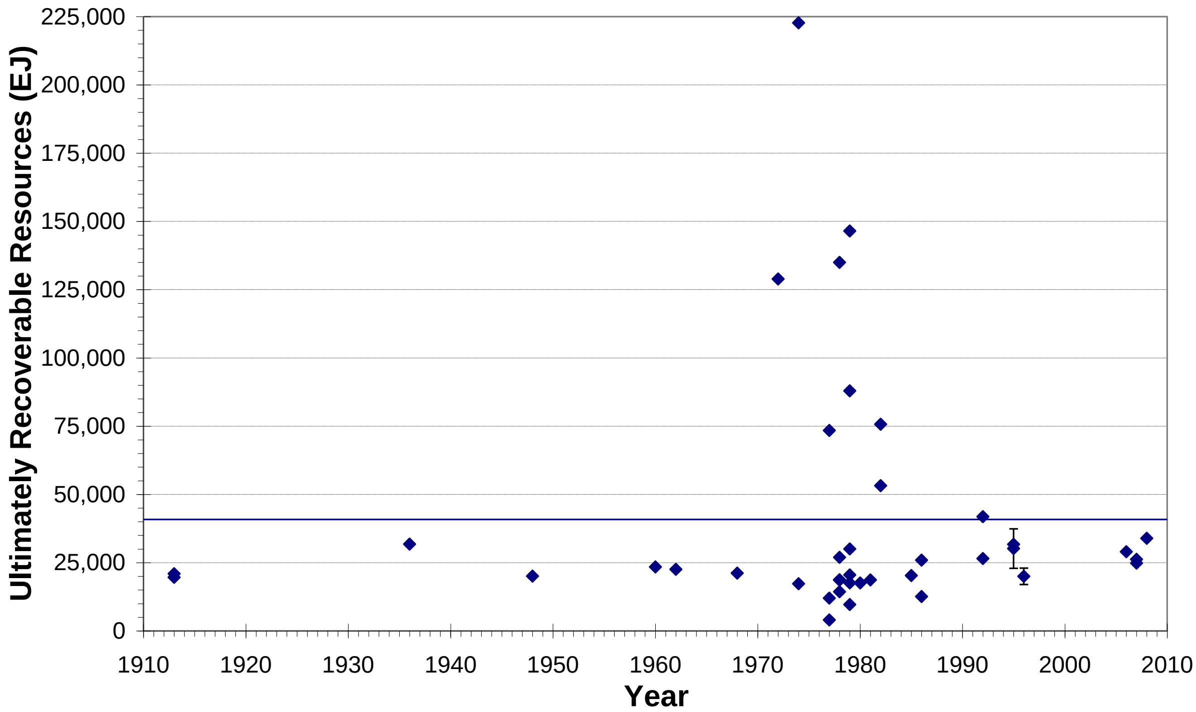


Figure 6-20. Estimates of ultimately recoverable resources of coal by various authors.
The mean value is marked by a line. The period between 1970 and 1985 saw a large increase in both the number and value of estimates, all estimates from outside this period lie below 50,000 EJ in value.

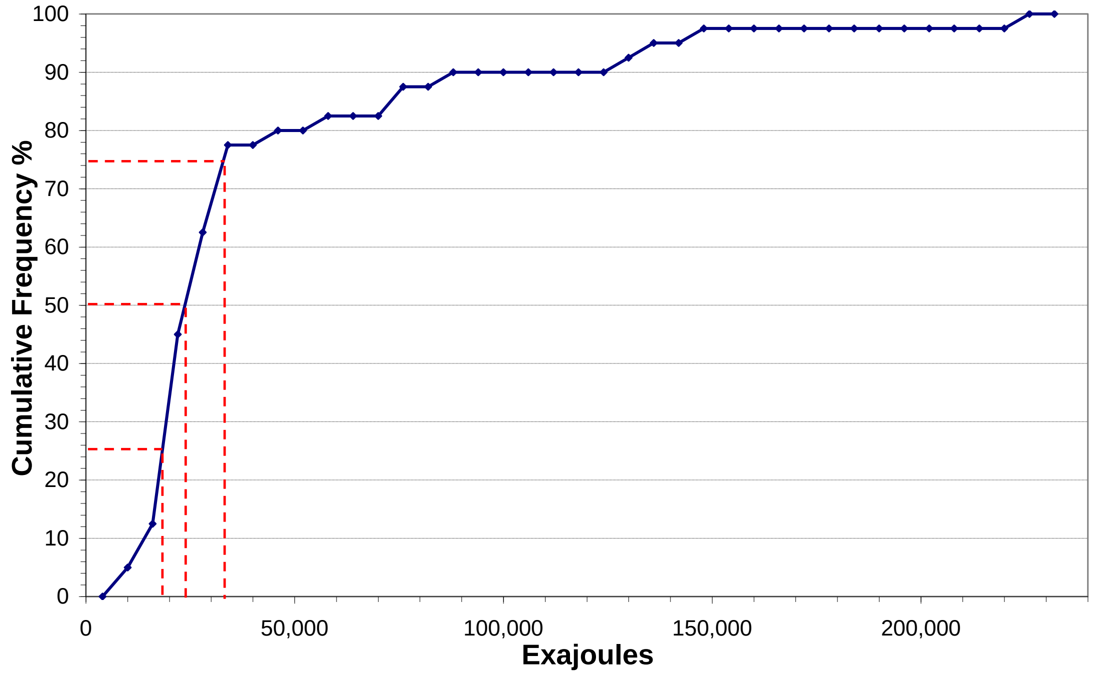


Figure 6-21. Cumulative frequency of estimates for ultimately recoverable resources of coal by various authors. The estimates are highly positively skewed, with the range of the fourth quartile being over four times larger than the sum of the first three.

Table 6-4. Values of statistical interest for the estimates of ultimately recoverable resources of coal

SAMPLE SIZE	40
COEFFICIENT OF VARIATION	1.0995
SKEWNESS	2.5679
EXCESS KURTOSIS	6.8927
	Exajoules
GRAND MEAN	40,815
GRAND STANDARD DEVIATION	44,877
STANDARD ERROR	7096
MODE	17,585
PERCENTILE	
Minimum	4015
5%	9791
10%	12,801
25%	18,691
MEDIAN	24,142
75%	33,398
90%	124,850
95%	145,960
Maximum	222,740
RANGE	218,723

Conventional oil

The study encompassed a total of 201 estimates ranging in time from 1942 to 2007. As with the estimates for coal, there are increased clusters of activity in certain periods, most notably in the period 1965-1980 and the period 1995 to the present (see Figure 6-22). These clusters also display a similarity of value, being between 6000-25000 EJ in the first period and 8000-29000 EJ in the second.

Although the distribution is much closer to a normal distribution than the estimates for coal, again there is some discrepancy amongst the estimates with the full range being around 50,000 EJ, whilst 75% of the estimates fall below 17,000 EJ (see Table 6-5 and Figure 6-23).

Table 6-5. Values of statistical interest for the estimates of ultimately recoverable resources of conventional oil in both SI units and billion barrels of oil

SAMPLE SIZE	201	
COEFFICIENT OF VARIATION	0.402	
SKEWNESS	2.248	
EXCESS KURTOSIS	11.075	
	Billion Barrels	Exajoules
GRAND MEAN	2144	14,072
GRAND STANDARD DEVIATION	1111	5660
STANDARD ERROR		399
MODE	2000	12,240
PERCENTILE		
Minimum		2754
5%		6405
10%		9792
25%		11,016
MEDIAN	2050	12,956
75%		16,409
90%		20,210
95%		24,345
Maximum		52,020
RANGE	8500	49,266

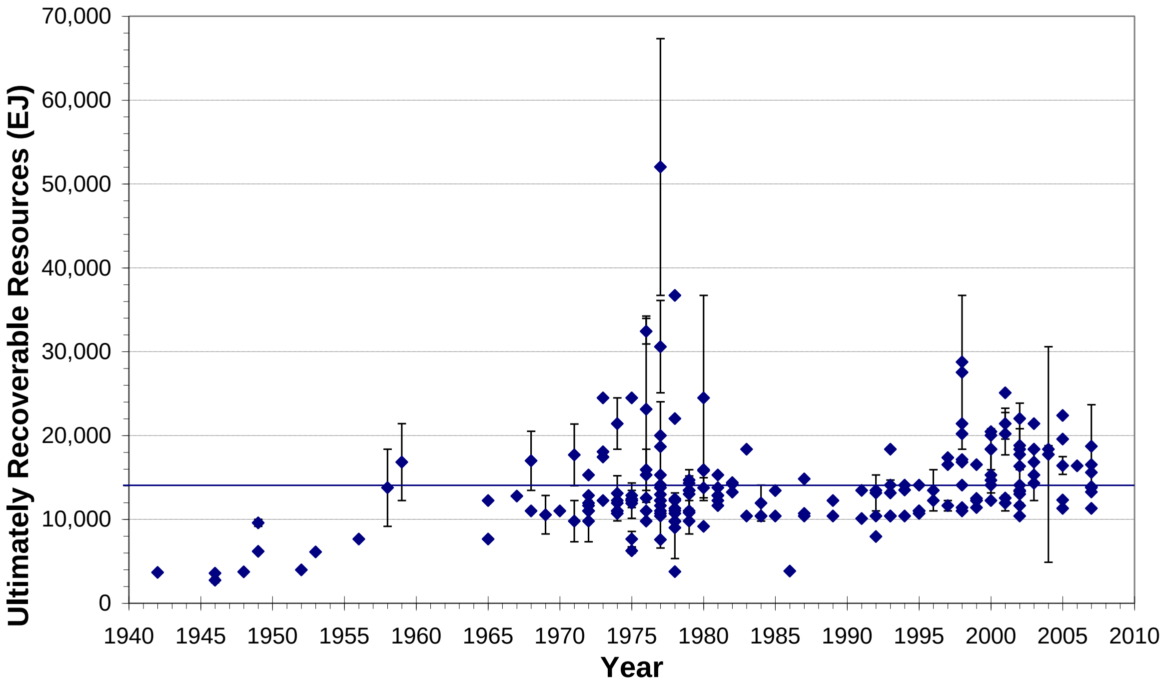


Figure 6-22. Estimates of ultimately recoverable resources of conventional oil by various authors.
There is an upward trend in the estimates over time with two distinct periods of increased frequency of estimates between 1965-1980 and then from 1995 to the present.

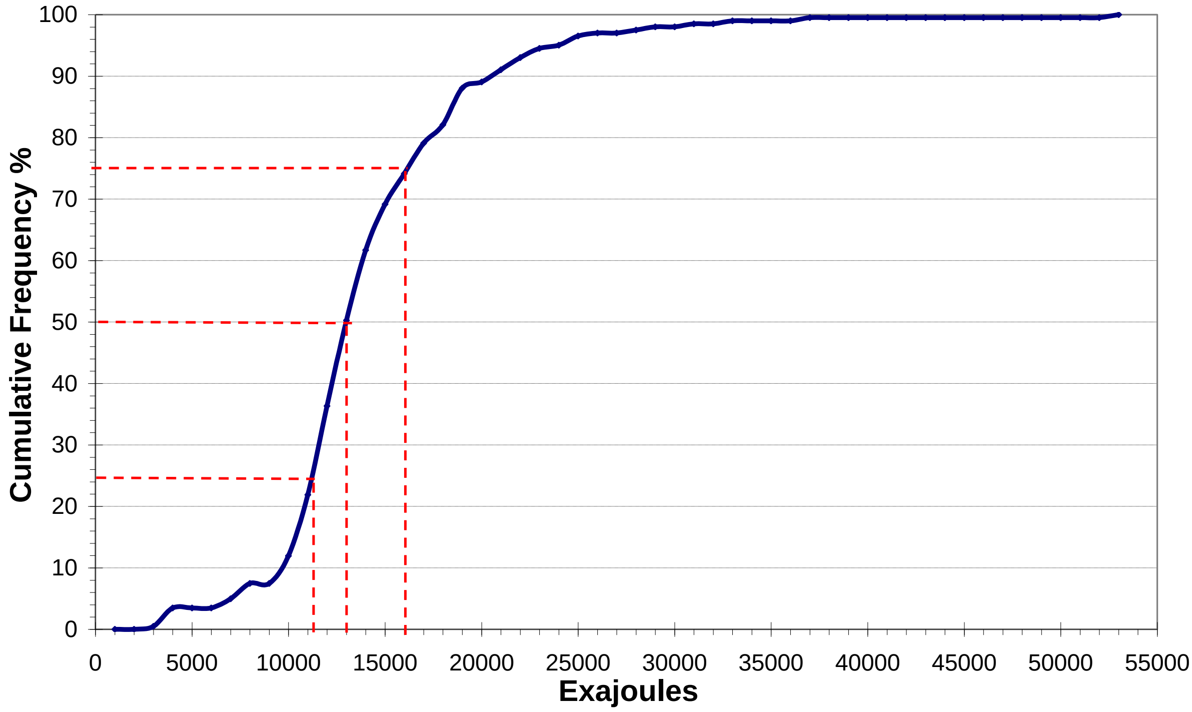


Figure 6-23. Cumulative frequency of estimates for ultimately recoverable resources of conventional oil by various authors.
Again the estimates are positively skewed, with the range of the fourth quartile being twice as large as the previous three put together.

Unconventional oil

The study located only 26 estimates for unconventional oil consisting of five distinct categories: natural gas liquids (NGL), deep-water and heavy oils, tar sands and oil shale. Again, interest in these 'alternative' energy sources was greatest in the period 1974-1985 (see Figure 6-24), presumably as a response to the oil shocks. There is an upward trend in the estimates of both tar sands and oil shale resources over time. The means of all estimates are: 2117 EJ for tar sands, 4303 EJ for oil shale, 1218 EJ for NGL, 339 EJ for heavy oil and 428 EJ for deep-water oil. The mean of estimates of total unconventional oil resources is 13,254 EJ.

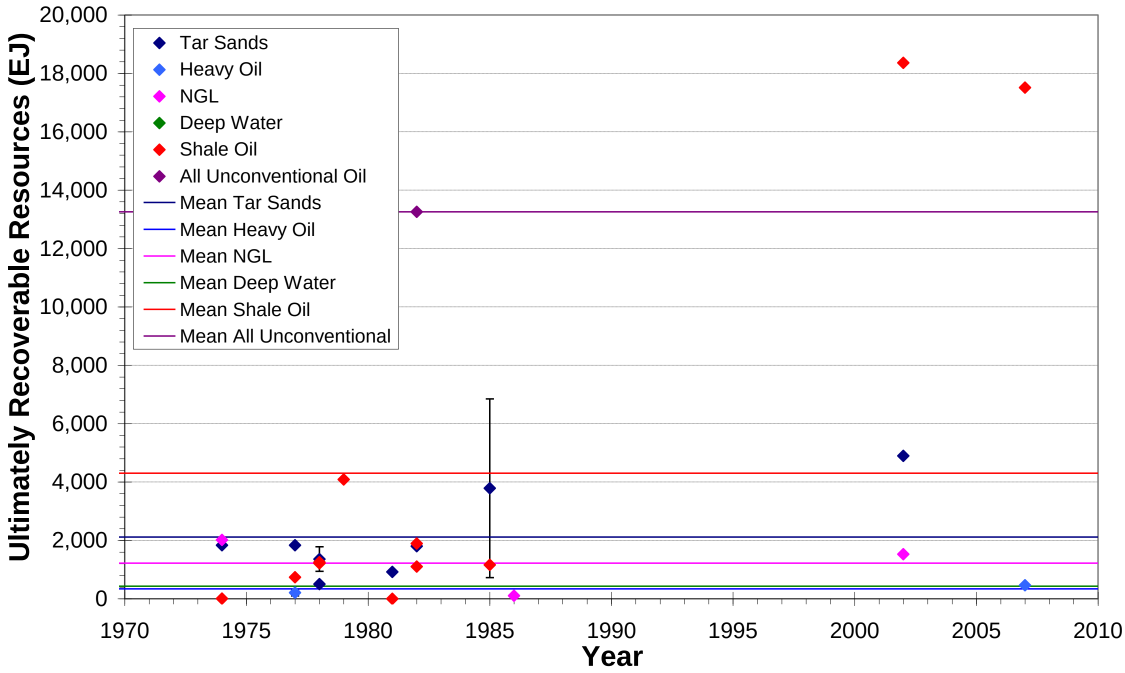


Figure 6-24. Estimates of ultimately recoverable resources of unconventional oil by various authors. The means of estimates are displayed as lines. There is an upward trend in estimates of oil shale and tar sands resources over time.

Conventional gas

This study located 70 estimates. Again, some clustering of estimates occurred between the years 1965-1985 and another between 1997 and 2005 and between 5,000-17,000 EJ in value (see Figure 6-25). The statistical values for the population (see Table 6-6) show that the mode is greater than the mean which is slightly greater than the median, indicating a reasonably close fit with a normal distribution. This is borne out by the shape of the cumulative frequency graph displayed in Figure 6-26.

Table 6-6. Values of statistical interest for the estimates of ultimately recoverable resources of conventional gas

SAMPLE SIZE	70
COEFFICIENT OF VARIATION	0.41206
SKEWNESS	1.1227
EXCESS KURTOSIS	2.9067
	Exajoules
GRAND MEAN	10,897
GRAND STANDARD DEVIATION	4404
STANDARD ERROR	532
MODE	12,240
PERCENTILE	
Minimum	1840
5%	4221
10%	5797
25%	7650
MEDIAN	10,500
75%	12,347
90%	17,136
95%	18,925
Maximum	28,764
RANGE	26,924

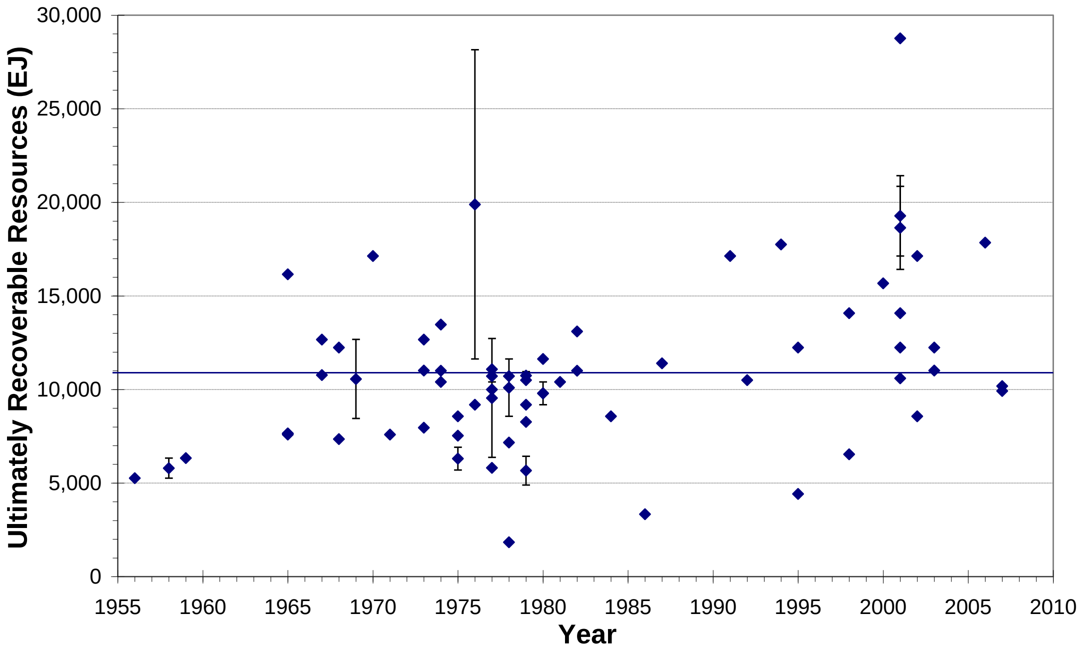


Figure 6-25. Estimates of ultimately recoverable resources of conventional gas by various authors.
There is an upward trend in estimates over the time period. Again there are clusters of estimates in the periods between 1965 and 1985 and again between 1995 and 2005.

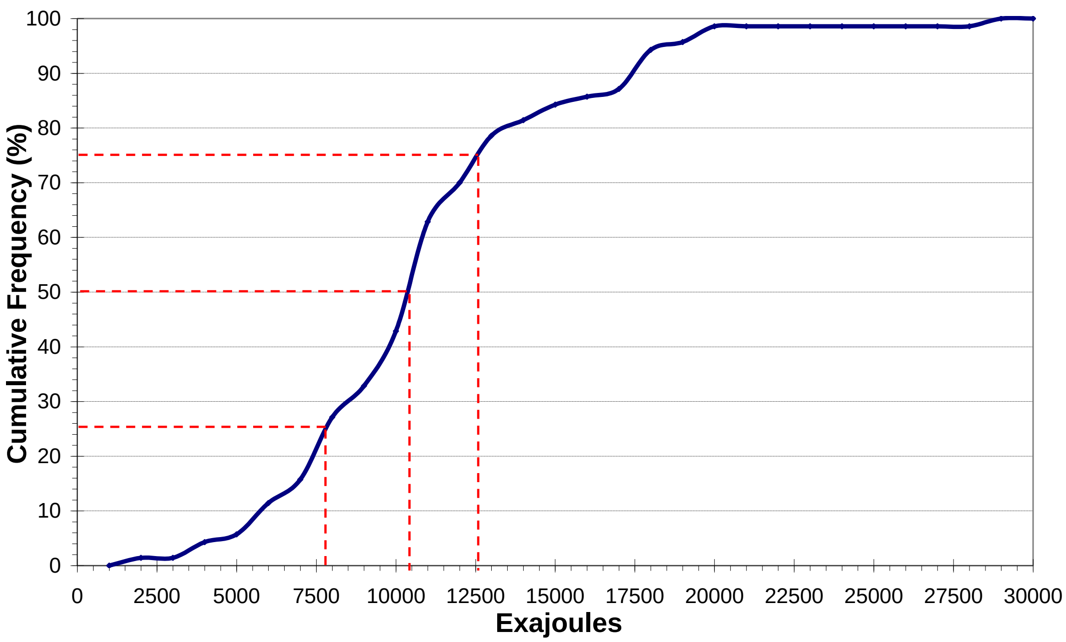


Figure 6-26. Cumulative frequency of estimates for ultimately recoverable resources of conventional gas by various authors.
The shape of the curve approximately resembles a normal distribution, with only slight positive skew.

Unconventional gas

This study could not locate enough estimates of ultimately recoverable resources of unconventional gas to generate any statistically interesting results (see Table 6-7).

Table 6-7. Estimates of the ultimately recoverable resources of unconventional gas

RESOURCE	YEAR	AUTHOR	ULTIMATELY RECOVERABLE (Billion barrels) unless stated	MEAN RECOVERABLE (EJ)	ERROR (EJ)
Tight Gas (coal seam)	1985	Edmonds & Reilly	370-860	3760	1500
Tight Gas (shale gas)	1986	Edmonds & Reilly	170-260	1320	280
Tight Gas	2002	Bentley	180	1100	0
Unconventional Gas	2001	Laherrere	2500 (Trillion cubic feet)	2650	0

Nuclear fission

This study located a total of 16 estimates for the ultimately producible amount of nuclear energy assuming that all ultimately recoverable resources of uranium are utilised in 'once-through' cycle 'burner' reactors yielding 173 TJ per tonne of U_3O_8.[35] (J. Edmonds & Reilly, 1985)

There is little clustering in the estimates (see Figure 6-27) and no obvious trend over time. The outlying estimate is over three times larger than the next largest estimate. The mean of all estimates is 1643 EJ. As can be seen from the mean, median and percentile values (see Table 6-8); the data is positively skewed and does not closely resemble a normal distribution (see Figure 6-28).

Table 6-8. Values of statistical interest for the estimates of ultimately producible nuclear energy

SAMPLE SIZE	16
COEFFICIENT OF VARIATION	1.3942
SKEWNESS	2.9646
EXCESS KURTOSIS	9.931
	Exajoules
GRAND MEAN	1643
GRAND STANDARD DEVIATION	2291
STANDARD ERROR	573
PERCENTILE	
Minimum	223
5%	223
10%	272
25%	360
MEDIAN	827
75%	2363
90%	4914
95%	9467
Maximum	9467
RANGE	9244

[35] 'Burner' reactors, such as pressurise water reactors (PWR) or boiling water reactors (BWR), are contrasted with so-called 'breeder' reactors, such as liquid metal fast breeder reactors (LMFBR), that are able to utilise natural (un-enriched) or even depleted uranium as a fuel to produce more fissionable products, such as plutonium, as a result of the reaction cycle.

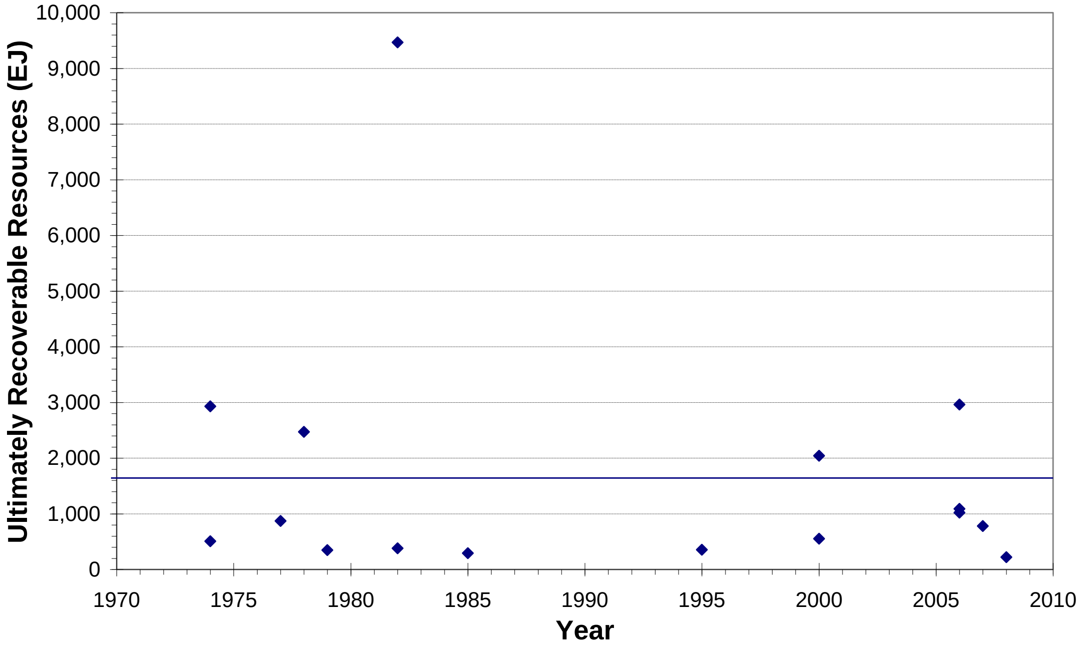


Figure 6-27. Estimates of ultimately producible nuclear energy by various authors. The mean value is displayed as a line. There is no obvious trend in the estimates. The outlying point is over three times larger than the next largest estimate.

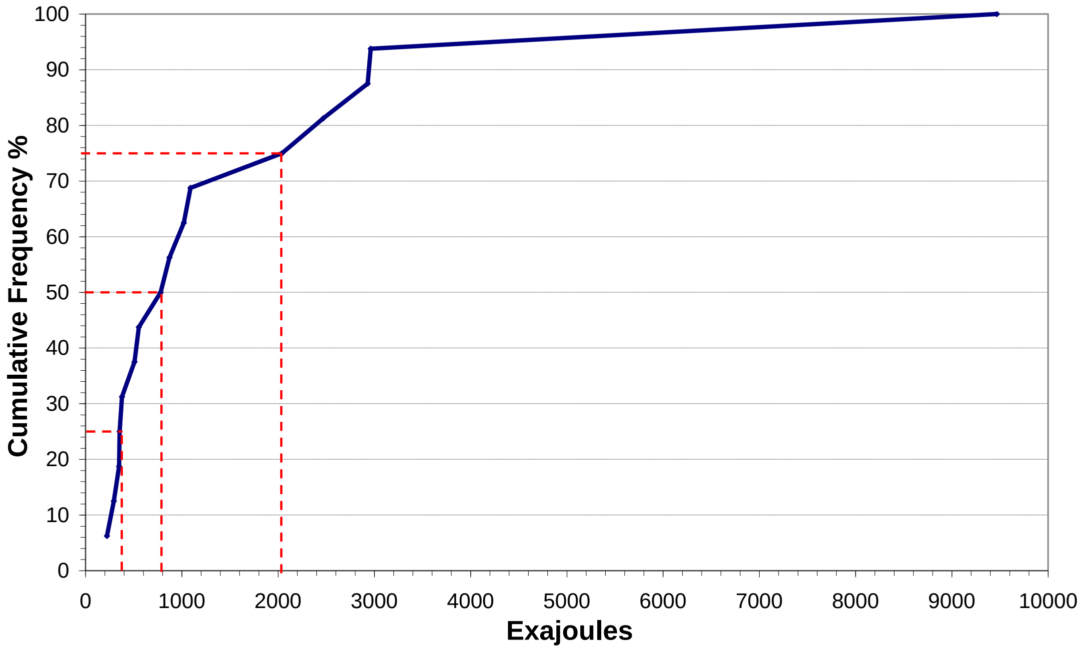


Figure 6-28. Cumulative frequency of estimates for ultimately producible nuclear energy by various authors. The estimates are positively skewed.

6.3.2. Renewable energy sources

There have been a great many attempts by authors to estimate the potential for individual renewable energy sources to supply energy for human purposes on a global scale.[36]

Classification of resources

As with non-renewable sources, there are many terms that are utilised in the literature (J. Edmonds & Reilly, 1985):

- ***Resource base*** **–** the maximum flow of energy per time period (normally a year). No presumption of being able to practically utilise the full amount is necessarily implied, often referred to as *theoretical potential* (Graßl, et al., 2004; M. Hoogwijk, de Vries, & Turkenburg, 2004).
- ***Recoverable resources*** **–** economic and technological feasibility criteria are specified, implying conditions under which some share of the resource base could be used, often further categorised as *technical* and *economic potential* (Graßl, et al., 2004; M. Hoogwijk, et al., 2004).
- ***Production capacity*** **–** the maximum amount of energy that could be produced during a given period, with the energy utilizing capital stock taken as fixed, sometimes called *installed* or *operating capacity* (WEA, 2000).
- ***Production*** **–** the amount of energy actually produced and used or stored in a useful form during a given time period.
- ***Remaining resources*** **–** resources not under production by a specified date
- ***Unexploited resources*** **–** an existing resource flow for which there is no production capacity (capital stock).

In the following analysis, estimates of the technical potential or recoverable reserves of each of the renewable energy sources individually are looked at, in order to determine suitable ranges for the values of the parameter TECHNICAL POTENTIAL.

[36] Although, admittedly, not as many as for non-renewable energy sources.

Biomass

There has been much interest in studying the energy production from biomass due to its potential to produce liquid fuels for the transport fleet whilst simultaneously combating Climate Change and oil depletion. This interest is reflected in the high number of estimates of the global potential of biomass production.

This study analyses 47 estimates. Looking at Figure 6-29 it can be seen that the estimates have a wide range, but that most of the estimates lie in the range 100 – 1000 EJ/yr. Again the population is positively skewed with 75% of estimates falling below 345 EJ/yr despite the range being over six times larger (see Table 6-9 and Figure 6-30). The mean of all estimates is 305 EJ/yr.

Table 6-9. Values of statistical interest for the estimates of technical potential of biomass

SAMPLE SIZE	47
COEFFICIENT OF VARIATION	1.339
SKEWNESS	2.4437
EXCESS KURTOSIS	5.578
	Exajoules
GRAND MEAN	371
GRAND STANDARD DEVIATION	497
STANDARD ERROR	72
MODE	189
PERCENTILE	
Minimum	2
5%	28
10%	45
25%	105
MEDIAN	189
75%	345
90%	1300
95%	1800
Maximum	2225
RANGE	2223

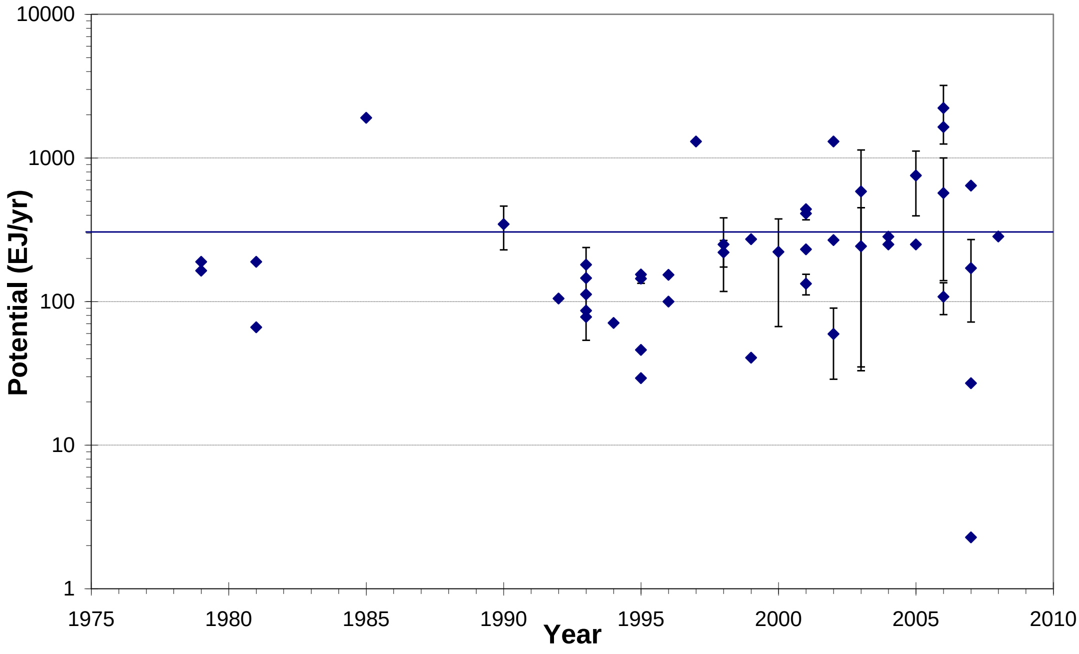


Figure 6-29. Estimates of the technical potential of biomass by various authors on a logarithmic plot. There is an upward trend in the estimates over time.

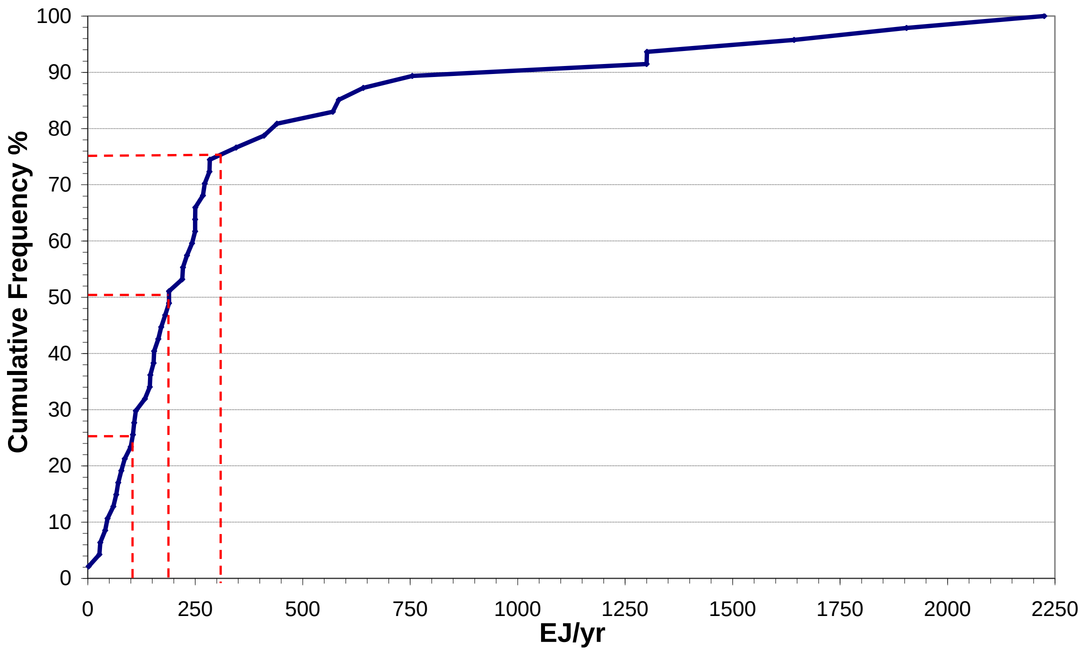


Figure 6-30. Cumulative frequency of estimates of technical potential of biomass by various authors

Hydro

This study located 32 estimates of the global potential of hydro power. There is little clustering of the estimates (see Figure 6-31), however, most of the estimates (~65%) lie under 70 EJ/yr. Looking at the values of statistical interest (see Table 6-10) and the cumulative frequency (see Figure 6-32) it can be seen that the population is positively skewed with the mean > median > mode. The mean of all estimates is 69 EJ/yr.

Table 6-10. Values of statistical interest for the estimates of technical potential of hydro

SAMPLE SIZE	32
COEFFICIENT OF VARIATION	0.62632
SKEWNESS	0.89891
EXCESS KURTOSIS	-0.17758
	Exajoules
GRAND MEAN	69
GRAND STANDARD DEVIATION	43
STANDARD ERROR	8
MODE	50
PERCENTILE	
Minimum	6
5%	13
10%	25
25%	39
MEDIAN	52
75%	103
90%	140
95%	159
Maximum	175
RANGE	169

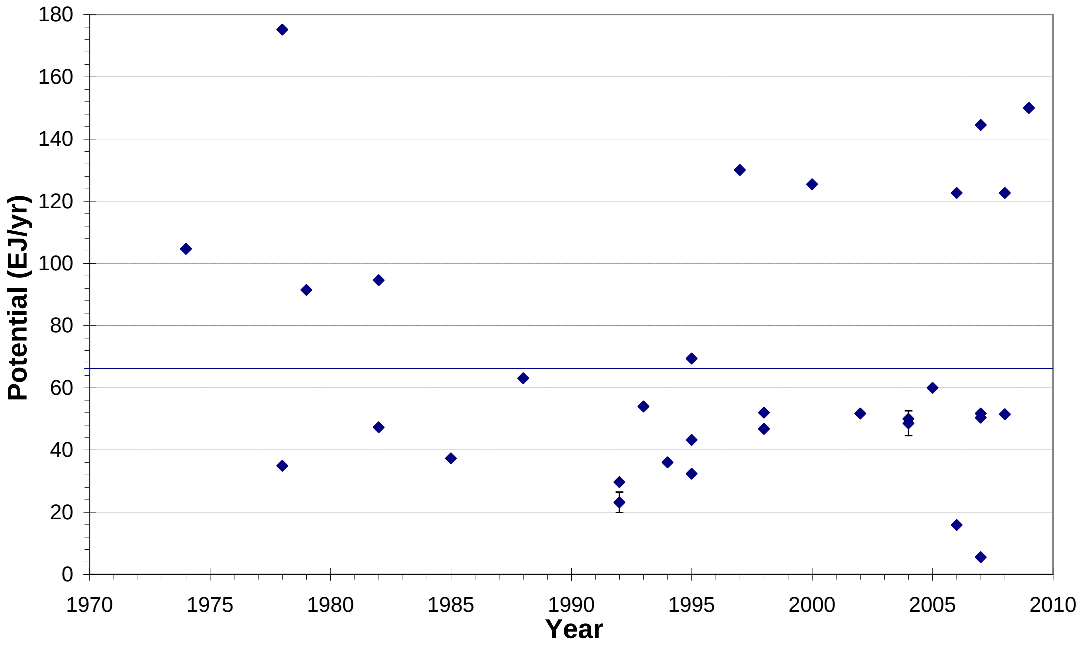


Figure 6-31. Estimates of technical potential of hydro by various authors
The mean value is marked by a line. There is a slight downward trend in the estimates over time

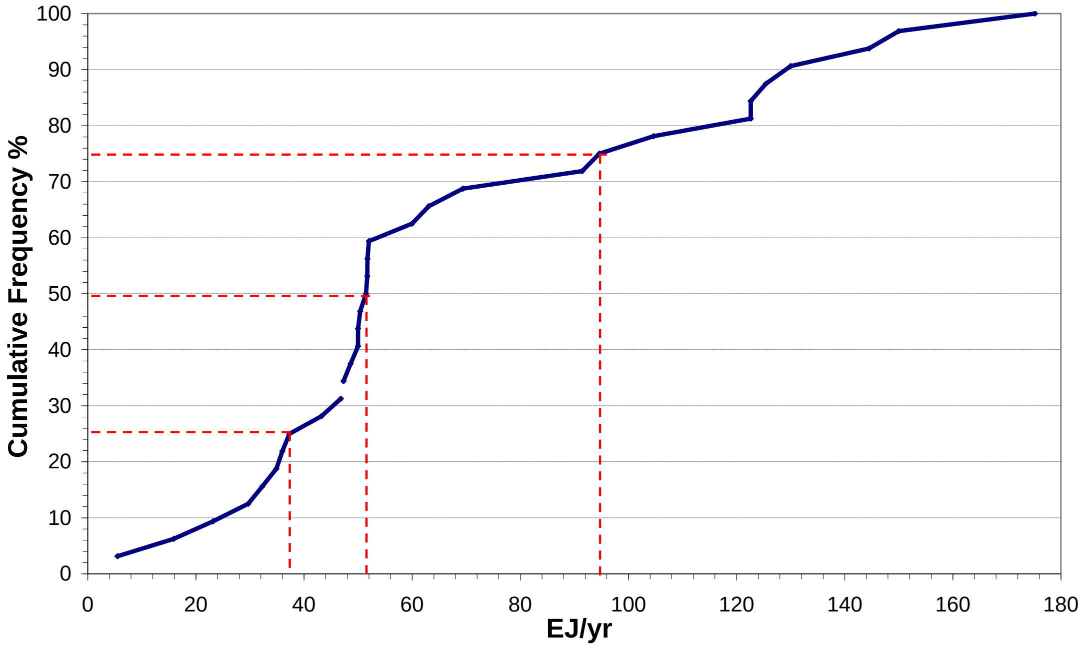


Figure 6-32. Cumulative frequency of estimates for technical potential of hydro by various authors.
The estimates are slightly positively skewed.

Geothermal

Despite the reservations of some authors (E. F. Cook, 1976) it is assumed that the geothermal resource can be utilised in a renewable manner. This study located 27 estimates of the global geothermal potential, of which 21 were for total geothermal energy production and 6 were of using geothermal for electricity generation, requiring a higher temperature than for direct heating uses. This analysis focuses on those estimates of the total geothermal potential.

There is a large range in the estimates (see Table 6-11) with clustering at both the high, over 1000 EJ/yr, and low, under 100 EJ/yr, ends (see Figure 6-33) reflected by steps in the cumulative frequency (see Figure 6-34). All of the estimates over the high threshold have been made since the year 2000 which may reflect an increase in the technical potential due to technological advances in so-called 'hot-dry rock' (Dickson & Fanelli, 2004) methods of production which allows more of the resource base to be utilised. The mean of all estimates is 1026 EJ/yr.

Table 6-11. Values of statistical interest for the estimates of technical potential of geothermal

SAMPLE SIZE	21
COEFFICIENT OF VARIATION	1.7161
SKEWNESS	1.7733
EXCESS KURTOSIS	1.8377
	Exajoules
GRAND MEAN	1026
GRAND STANDARD DEVIATION	1761
STANDARD ERROR	384
MODE	5000
PERCENTILE	
Minimum	1
5%	1
10%	2
25%	16
MEDIAN	63
75%	1401
90%	5000
95%	5000
Maximum	5000
RANGE	4999

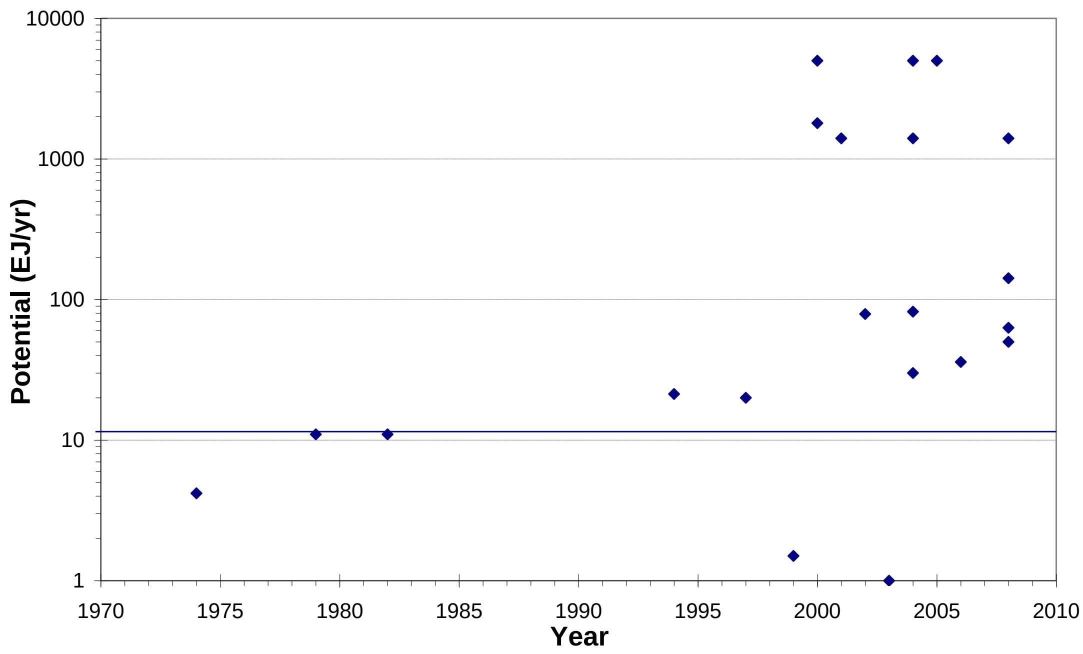


Figure 6-33. Estimates of technical potential of geothermal by various authors on a logarithmic plot with the mean value displayed as a line.
There is an upward trend in both the frequency and value of estimates over time.

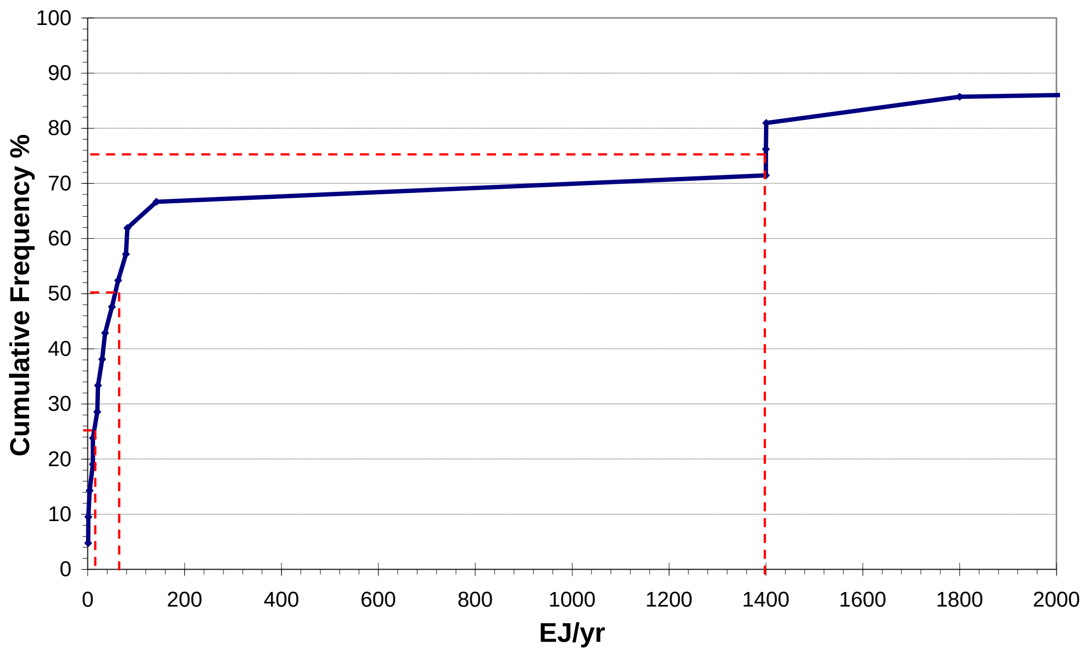


Figure 6-34. Cumulative frequency of estimates of technical potential of geothermal by various authors.
The estimates show two distinct groups of estimates perhaps reflecting the introduction of technologies utilising 'hot-dry rock' thus enlarging the usable resource.

Tidal

This study located 11 estimates of the global technical potential of tidal energy. The range of the estimates is very much smaller than that of most of the other energy sources but, again, there is a positive skew (see Figure 6-35 and Figure 6-36 and Table 6-12). There is an upward trend in the estimates over time. The mean of all estimates is just over 2 EJ/yr

Table 6-12. Values of statistical interest for the estimates of technical potential of tidal energy

SAMPLE SIZE	11
COEFFICIENT OF VARIATION	1.2776
SKEWNESS	2.6939
EXCESS KURTOSIS	7.6549
	Exajoules
GRAND MEAN	3
GRAND STANDARD DEVIATION	4
STANDARD ERROR	1
MODE	1
PERCENTILE	
Minimum	1
5%	1
10%	1
25%	1
MEDIAN	1
75%	3
90%	11
95%	13
Maximum	13
RANGE	12

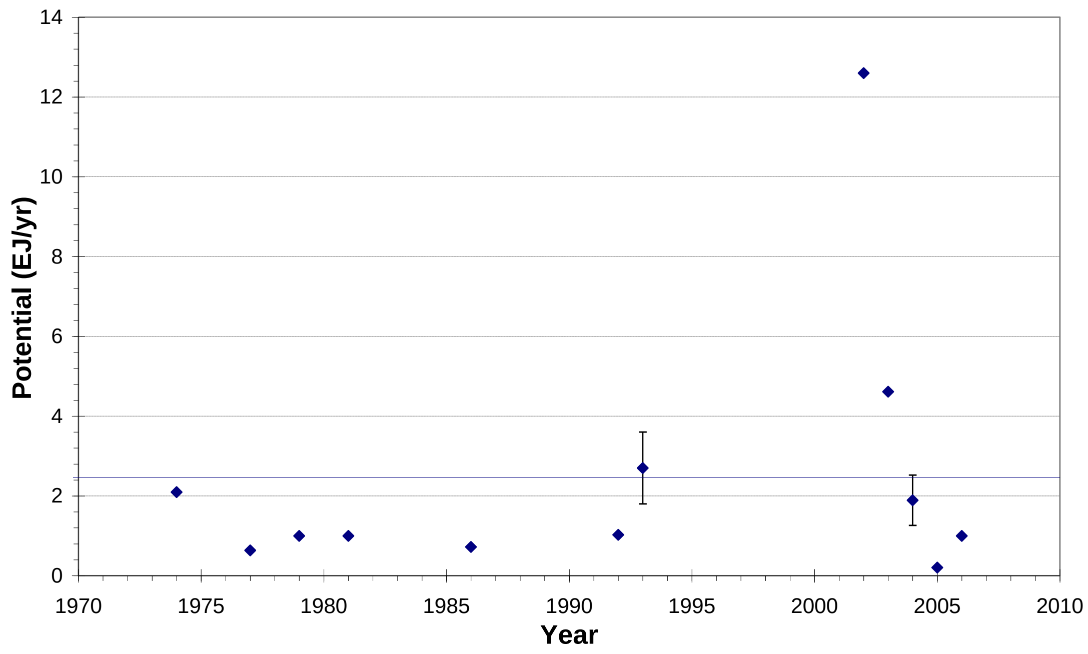


Figure 6-35. Estimates of the technical potential of tidal energy by various authors with the mean value plotted. There is a slight upward trend in the estimates over time.

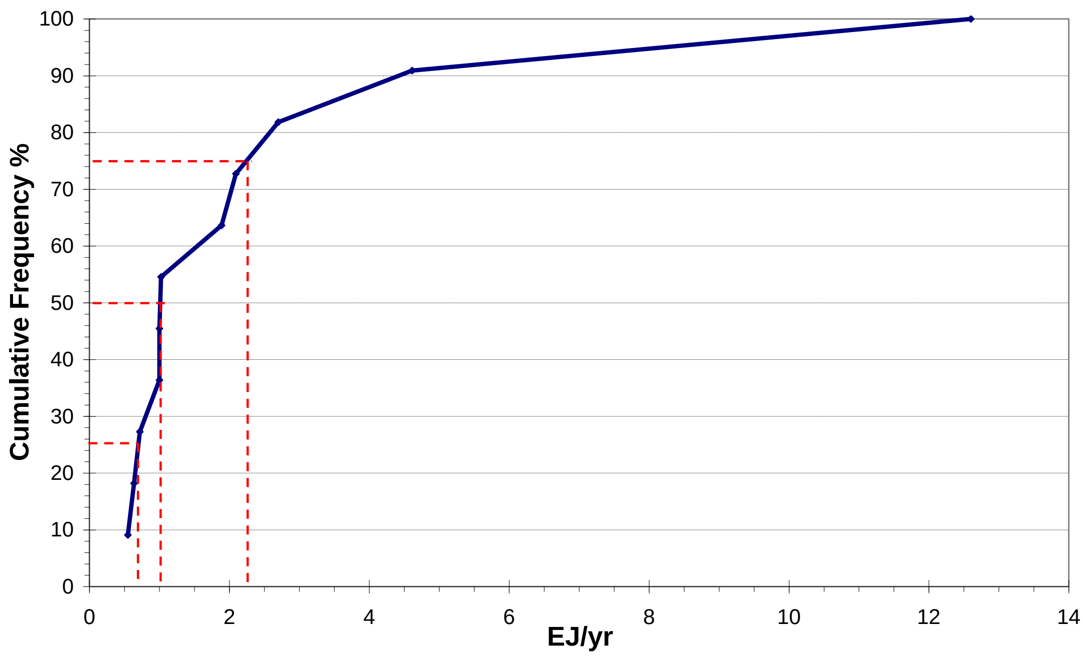


Figure 6-36. Cumulative frequency of estimates of technical potential of tidal energy by various authors. The estimates are positively skewed with the full range over twelve times larger than the median value.

Wind

This study located 26 estimates of the global wind energy resource potential. There is some consistency in all but one of the estimates (see Figure 6-37) which is larger than the next lowest estimate by a factor of 8 times. This estimate is left out in further analysis.

A first look at the remaining estimates shows that they fall roughly into three groups (see Figure 6-38): the lowest consisting of those estimates below 200 EJ/yr, wherein lie the majority of estimates; the middle group makes up around a quarter of the total and lies in the range 340-450 EJ/yr; and the highest (and smallest) group which lies around 600 EJ/yr.

The percentile ranges and the cumulative frequency (see Table 6-13 and Figure 6-39) show more evidence of the unusual distribution of the population, in that 60% lie under 220 EJ/yr yet the remaining estimates arrive in a series of sharp steps indicating the grouping discussed earlier. The mean of the estimates (excluding the outlier) is 258 EJ/yr.

Table 6-13. Values of statistical interest for the estimates of technical potential of wind

SAMPLE SIZE	25
COEFFICIENT OF VARIATION	0.77207
SKEWNESS	0.70528
EXCESS KURTOSIS	-0.66854
	Exajoules
GRAND MEAN	240
GRAND STANDARD DEVIATION	185
STANDARD ERROR	37
MODE	95
PERCENTILE	
Minimum	19
5%	23
10%	34
25%	95
MEDIAN	185
75%	366
90%	588
95%	600
Maximum	600
RANGE	581

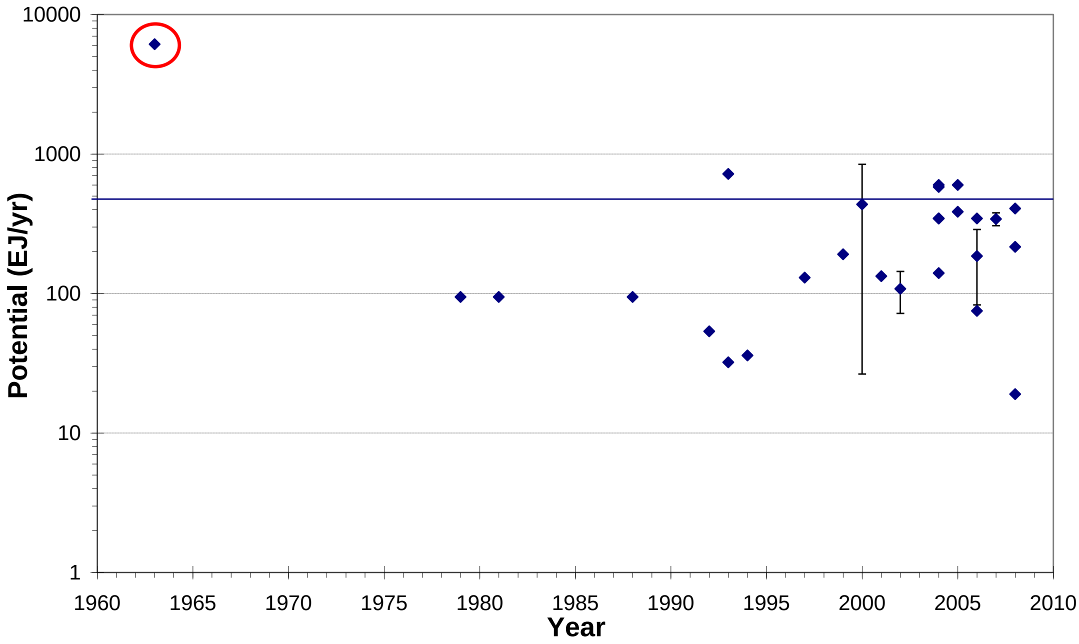


Figure 6-37. Estimates of technical potential of wind by various authors on a logarithmic plot. An outlying estimate is circled and the mean value is plotted.

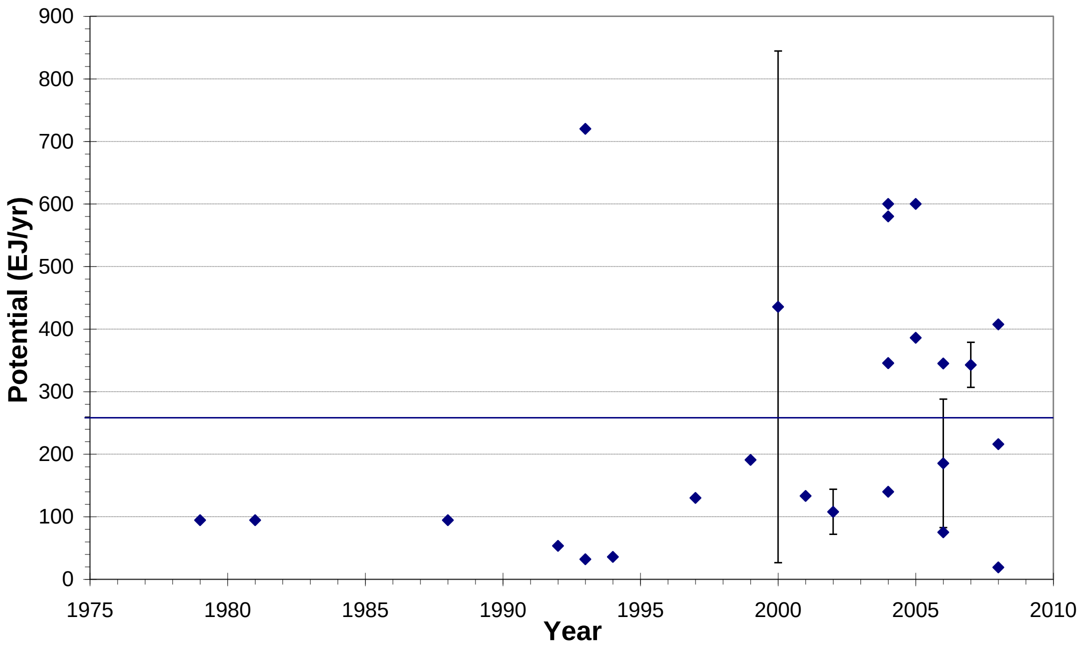


Figure 6-38. Estimates of technical potential of wind energy by various authors. The outlying estimate has been removed and a new mean plotted. There is an upward trend in both the frequency and value of estimates over time.

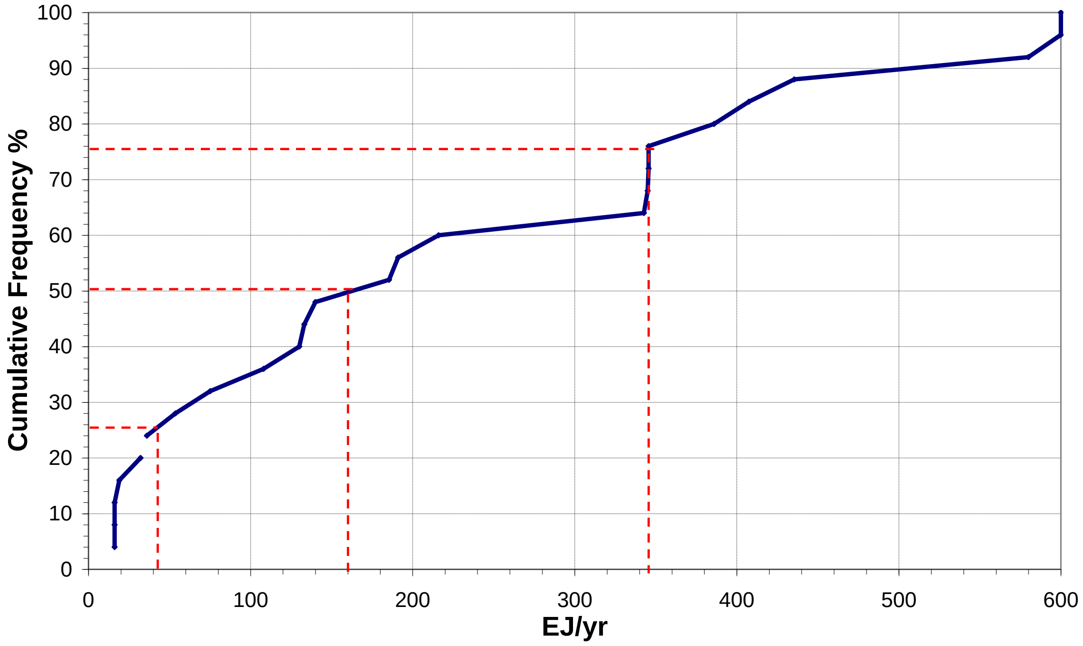


Figure 6-39. Cumulative frequency of estimates of technical potential of wind energy by various authors. The estimates display a distinct grouping between the ranges of 340-450 EJ/yr and a further group around 600 EJ/yr

Solar

Solar energy is often thought of as a vast, untapped global resource. Such statements as, "yearly, the Earth receives 6000 times more sunlight energy than humans consume" (NREL, 2000) offer visions of unlimited abundance. As discussed previously, in reality the solar resource, whilst large, is so diffuse that it is difficult to utilise without large collectors.

This study found 24 estimates relating to the technical potential of the solar resource, consisting of 6 estimates of the potential of PV, 5 for solar thermal, 1 relating to solar thermal electric concentrating (STEC) systems and 12 estimates of the total technical potential of all solar sources.

There is a huge variation in the estimates by a factor of nearly 10,000 from smallest to largest (see Figure 6-40); however, the majority of the estimates lie under 1000 EJ/yr.

Table 6-14 Values of statistical interest for the estimates of technical potential of solar energy production

	All Solar	**PV**	**Solar Thermal**
SAMPLE SIZE	9	6	5
COEFFICIENT OF VARIATION	2.2037	1.9053	2.1043
SKEWNESS	2.5996	2.3885	2.2347
EXCESS KURTOSIS	6.8863	5.7628	4.9953
	exajoules	exajoules	exajoules
GRAND MEAN	13038	4860	2595
GRAND STANDARD DEVIATION	28733	9259	5461
STANDARD ERROR	9578	3780	2442
MODE			
PERCENTILE			
Minimum	57	43	11
5%	57	43	11
10%	57	43	11
25%	90	81	99
MEDIAN	888	1330	186
75%	14153	7945	6296
90%	86400	23652	12362
95%	86400	23652	12362
Maximum	86400	23652	12362
RANGE	86343	23609	12351

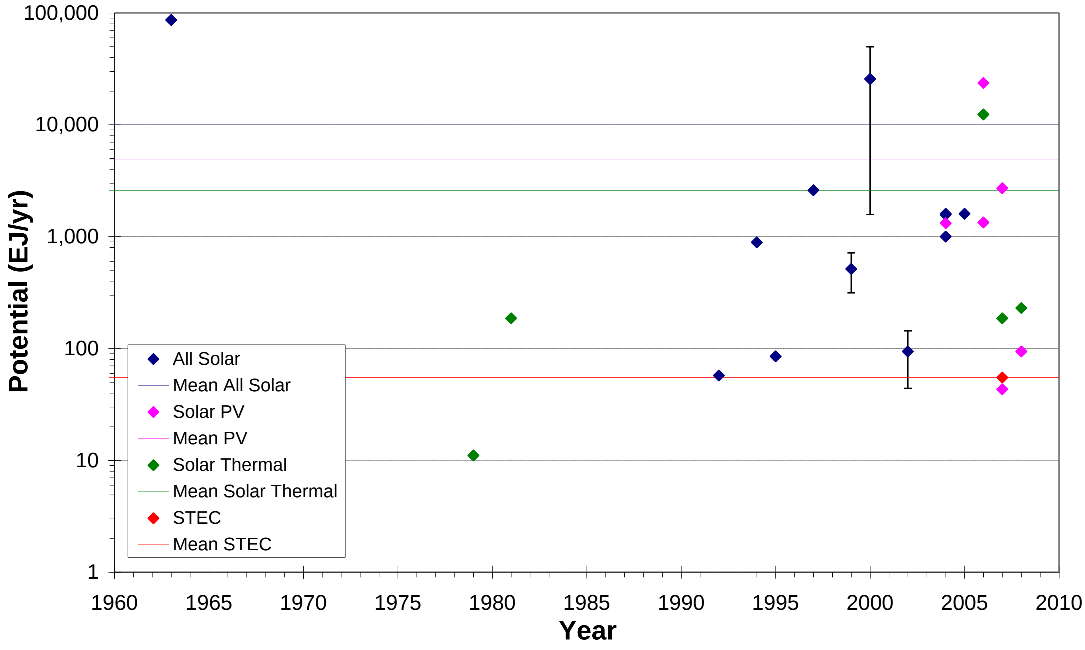


Figure 6-40. Estimates of technical potential of solar by various authors on a logarithmic scale
The mean value of estimates is plotted. There is downward trend in the value of estimates of total solar resources; however solar thermal estimates display an upward trend over the time period.

All ocean

Due to the lack of estimates regarding the ocean-based energy sources: tidal, wave and OTEC, these estimates have been put into a single group. The estimates are displayed in Figure 6-41. All of the sub-groups exhibit an upward trend over the time period. The mean of the estimates are: 3 EJ/yr for tidal energy, 10 EJ/yr for wave, 67 EJ/yr for OTEC and 153 EJ/yr for estimates of total ocean energy resource.

Table 6-15 Values of statistical interest for the estimates of technical potential of ocean energy production

	All Ocean	**Wave**	**OTEC**
SAMPLE SIZE	5	10	6
COEFFICIENT OF VARIATION	2.1014	1.9331	1.3523
SKEWNESS	2.2333	3.0061	1.719
EXCESS KURTOSIS	4.9901	9.2461	2.795
	exajoules	exajoules	exajoules
GRAND MEAN	153	10	67
GRAND STANDARD DEVIATION	322	20	90
STANDARD ERROR	144	6	37
MODE			
PERCENTILE			
Minimum	<1	<1	<1
5%	<1	<1	<1
10%	<1	<1	<1
25%	4	2	2
MEDIAN	10	4	32
75%	375	9	134
90%	730	60	237
95%	730	65	237
Maximum	730	65	237
RANGE	730	65	237

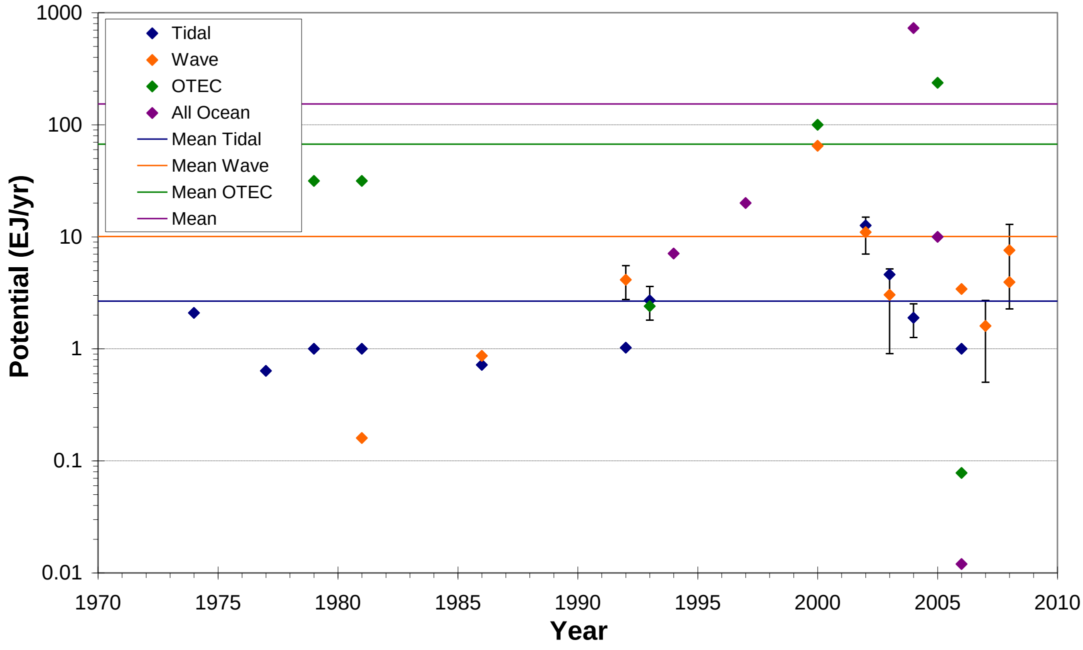


Figure 6-41. Estimates of technical potential of all ocean energy by various authors.
The mean values are plotted. There is an upward trend in the values of estimates of all sources over time.

6.3.3. Summary

To conclude this section, the aggregation of the main parameters for each of the energy resources is presented in Table 6-16 and Table 6-17. If it is assumed that the estimates for each resource are normally distributed, then the total value of ultimately recoverable fossil and fissile energy resources is 70,592 EJ; if, on the other hand, the best fitting distribution from each of the resource estimate populations is used, a total value of 50,702 EJ is determined, a factor of around 30% smaller.

Assuming normal distributions, a value for the total technical potential of all renewable energy sources is 8565 or 8587 EJ/yr (depending on whether or not the ocean energy sources are aggregated). If the other distributions offered by the fitting procedure are used, we obtain a value of 993 or 994 EJ/yr (again depending on whether or not the estimates for ocean energy are aggregated). The discrepancy between these two figures is a factor of over eight. Much of this is due to the small population sizes of the estimates. However, some of the discrepancy is due to the indeterminacy of the technology involved since many of the designs are not in commercial operation and so estimation of the technical potential depends very much on assumptions about the improvement of the technology.

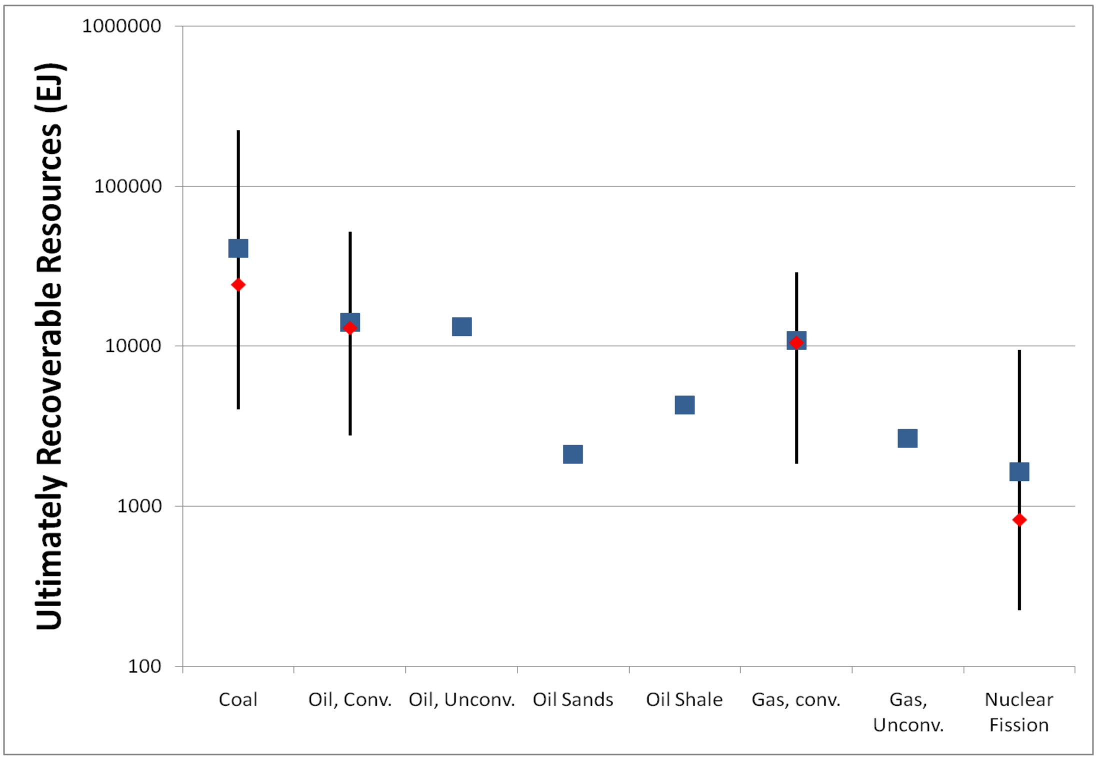


Figure 6-42 URR of non-renewable energy sources.
Squares represent mean (blue) and median (red) of all estimates; vertical lines represent the range of estimates.

Table 6-16. Summary of distribution parameters for various non-renewable energy sources

COAL:			
Normal	μ = 40,815	σ = 44,877	
GEV	μ = 20,499	σ = 11,790	
CONVENTIONAL OIL			
Normal	μ = 14072	σ = 5660	
Log-Logistic	β = 18,057	α = 7.116	γ = -477.4
UNCONVENTIONAL OIL			
Normal	μ = 3165	σ = 5074	
Frechet	β = 1278	α = 1.2498	γ = -455.04
CONVENTIONAL GAS			
Normal	μ = 10,897	σ = 4404	
Cauchy	μ = 10,257	σ = 1990	
NUCLEAR FISSION			
Normal	μ = 1643	σ = 2291	
Fatigue Life	β = 611	α = 1.675	γ = 181.85
TOTAL			
Normal	**μ = 70,592 EJ**	**σ = 45,786 EJ**	
Other Distributions	**μ = 50,702 EJ**		

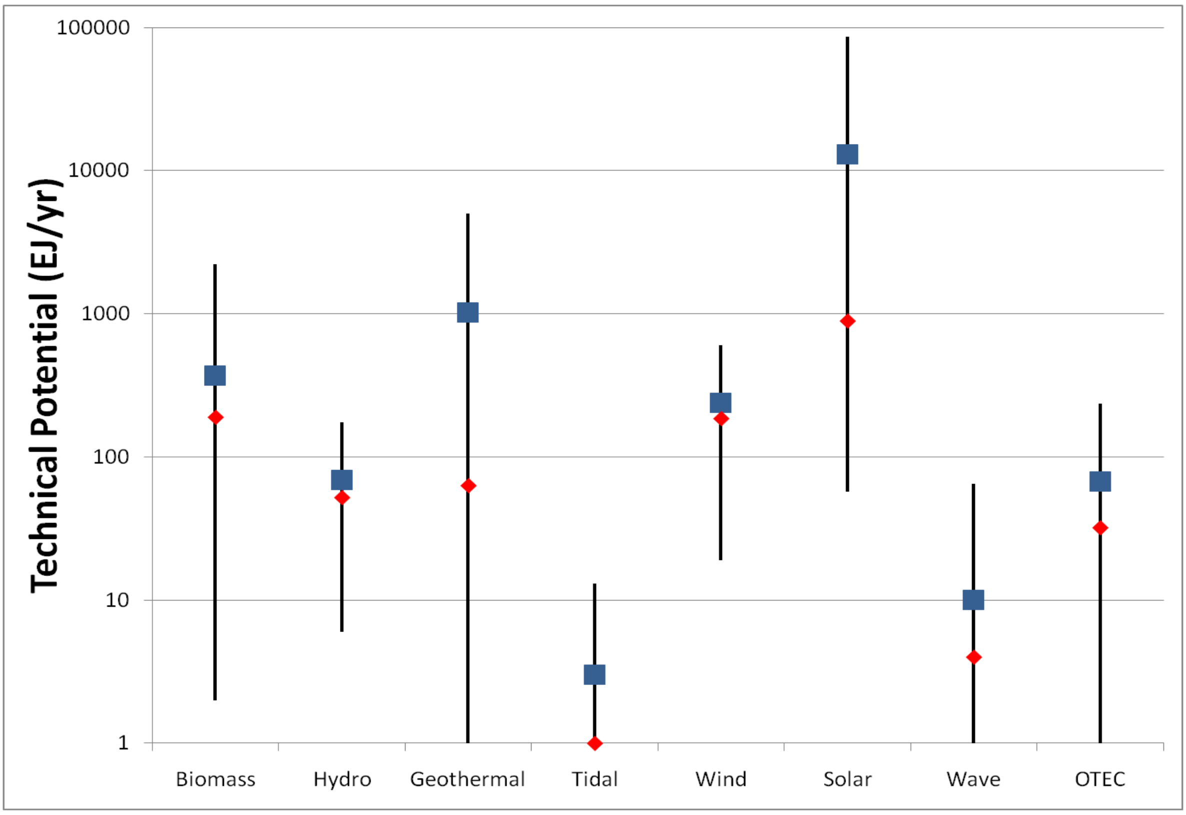


Figure 6-43 TP of renewable energy sources.
Squares represent mean (blue) and median (red) of all estimates; vertical lines represent the range of estimates.

Table 6-17. Summary of distribution parameters for various renewable energy sources

BIOMASS			
Normal	μ = 371	σ = 497	
GEV	μ = 144	σ = 144	k = 0.51015
HYDRO			
Normal	μ = 69	σ = 43	
GEV	μ = 48	σ = 30	k = -0.17758
GEOTHERMAL			
Normal	μ = 1026	σ = 1761	
Fatigue Life	μ = 173	σ = 457	k = 0.57159
TIDAL			
Normal	μ = 3	σ = 1	
GEV	μ = 1	σ = 1	k = 0.72832
WIND			
Normal	μ = 240	σ = 185	
GEV	μ = 149	σ = 143	k = 0.05719
PV			
Normal	μ = 4859	σ = 9259	
Lognormal	μ = 7	σ = 2	
SOLAR THERMAL			
Normal	μ = 2595	σ = 5461	
Cauchy	μ = 192	σ = 38	
ALL SOLAR			
Normal	μ = 13038	σ = 28733	
Lognormal	μ = 7	σ = 2	
WAVE			
Normal	μ = 10	σ = 20	
Frechet	β = 3	α = 1	γ = -1.0482
OTEC			
Normal	μ = 91	σ = 67	
Log-Pearson 3	μ = 15	σ = 31	k = 0.53329
ALL OCEAN			
Normal	μ = 153	σ = 322	
Cauchy	μ = 8	σ = 7	
TOTAL			
Normal	**9264– 14900 EJ/yr** [a]		
Other distributions	**530 – 732 EJ/yr**		

a The range is due to the aggregation or not of ocean and solar resources

CHAPTER 7. RESULTS AND ANALYSIS

In this chapter, the GEMBA model results are presented and discussed.

The first section deals with calibration of the model parameters to historical data. The second section presents the results of sensitivity analyses of the TOTAL ENERGY YIELD and NET INDUSTRIAL OUTPUT to changes in the main parameters characterising each energy source:

- availability of the energy source, represented by URR (non-renewable) or TP (renewable);
- the PEAK EROI;
- the INCEPT DATE and;
- the capital intensity represented by the parameter CAPITAL FACTOR.

The final section looks at the sensitivity of the NET INDUSTRIAL OUTPUT and TOTAL ENERGY YIELD to changes in the parameter ENERGY REQUIREMENT RATIO which represents the energy intensity of the economy.

7.1. Calibration to historical data

Historic production data for mature technologies was used to calibrate the model, using the following steps:

1. Use values found from the meta-analysis as initial starting values for the parameters URR_k or TP_k, PEAK EROI_k, INCEPT DATE_k, Ξ_k, ξ_k and $\boldsymbol{\phi}_k$ (as displayed in Table 7-1);
2. Run the calibration procedure to obtain the best-fit between model output ENERGY PRODUCTION_k and historic data for that energy source by varying parameters URR_k or

TP$_k$, PEAK EROI$_k$, INCEPT DATE$_k$, Ξ_k, ξ_k, ϕ_k, INDUSTRIAL CAPITAL EFFECTIVENESS and ENERGY REQUIREMENT RATIO.

3. Analyse the parameter values in comparison with the meta-analysis data (a 'reality check').

Since no data exists for the energy sources UNCONVENTIONAL GAS, WAVE and OTEC, the parameters for these sources was assumed, as shown in Table 7-2. LIFETIME of all CAPITAL STOCK was assumed to be 20 years. The CAPITAL FACTOR of energy sources was assumed to be 0.1 for non-renewable and 0.9 for renewable sources. Model parameter Φ_k was assumed to be 1.

The model output ENERGY PRODUCTION$_k$ for each energy source was calibrated to the historic production data for that energy source, within the context of the whole model structure – for instance, changing the value of EROI for COAL PRODUCTION will affect the amount of OIL PRODUCTION, since ENERGY DEMAND$_k$ will be diverted from one to the other. The values used for historical production represent the mean of all estimates for that energy source (see Appendix A for the tabulated data).

The calibration procedure is an inbuilt function within VenSim. An optimisation algorithm finds the minimum value of the residual sum of squares between the model output ENERGY PRODUCTION$_k$ and historic production data for that energy source, by varying the value of the input parameters, URR$_k$ or TP$_k$, PEAK EROI$_k$, INCEPT DATE$_k$, Ξ_k, ξ_k and ϕ_k. The results from the calibration are shown in Table 7-3.

Comparing the values obtained for URR$_k$ and TP$_k$ with the values from the meta-analysis finds:

- The calibration value for URR$_{COAL}$ is close in value to the 75% quartile (33,398 EJ) of all estimates.
- The calibration value for URR$_{OIL, CONVENTIONAL}$ is close to the 60% percentile of all estimates.
- The calibration value for URR$_{OIL, UNCONVENTIONAL}$ is somewhat lower than the one estimate for URR of all unconventional oil (13,254 EJ), however is comparable to the sum of means of estimates for heavy oil, NGL, deep water and tar sands (4102 EJ).
- The calibration value for URR$_{GAS, CONVENTIONAL}$ is within 15% of the median of all estimates (10,500 EJ).
- The calibration value for TP$_{BIOMASS}$ is below the 25% quartile value (105 EJ/yr) and is only30% greater than the present value of biomass production (50 EJ/yr in 2007).
- The calibration value for TP$_{HYDRO}$ is close to the 25% quartile value (39 EJ/yr).

- The calibration value for $TP_{GEOTHERMAL}$ is around the 70% percentile of all estimates.
- The calibration value for TP_{TIDAL} is equal to the median value.
- The calibration value for TP_{WIND} and TP_{SOLAR} were unchanged by the calibration method.

The value of $EROI_k$ is plotted with the estimates of EROI for the three fossil fuels, coal conventional oil and conventional gas in Figure 7-5 to Figure 7-7. The output from the GEMBA model falls within the range of estimates of the EROI for each of these energy sources.

The model output ENERGY PRODUCTION of the three main fossil fuels (coal, conventional oil and conventional gas) are plotted in Figure 7-1, Figure 7-2 and Figure 7-3 with historical production data for comparison. The model output corresponds well in most cases (although some better than others) as attested by the different R^2 for each of the energy sources in Table 7-3. The model output total energy yield is plotted with historic data in Figure 7-1.

Hereafter, these parameter values and the values of model variables derived from them are used as a baseline for comparison of various sensitivity analysis scenarios.

Table 7-1. Initial values of model parameters before calibration procedure

Energy Source	**URR [EJ] or TP [EJ/yr]**	**PEAK EROI [dmnl]**	**INCEPT DATE [yr]**	**Ξ [dmnl]**	**ξ [dmnl]**	**ϕ [dmnl]**
COAL	25000	210	1800	0.8	4	1.75
OIL, CONVENTIONAL	14000	425	1860	0.8	4	1.75
OIL, UNCONVENTIONAL	2800	15	1880	0.8	4	1.75
GAS, CONVENTIONAL	13500	200	1880	0.8	4	1.75
NUCLEAR FISSION	1500	15	1955	0.8	4	1.75
BIOMASS	200	20	1800	0.8	4	1.75
HYDRO	25	30	1900	0.8	4	1.75
GEOTHERMAL	300	10	1955	0.8	4	1.75
TIDAL	2	20	1970	0.8	4	1.75
WIND	175	30	1970	0.8	4	1.75
SOLAR	750	10	2000	0.8	4	1.75
ENERGY REQUIREMENT RATIO	3					
CAPITAL EFFECTIVENESS	0.1					

Table 7-2 Parameter values assumed for UNCONVENTIONAL GAS, WAVE and OTEC

Energy Source	URR [EJ] or TP [EJ/yr]	PEAK EROI [dmnl]	INCEPT DATE [yr]	Ξ [dmnl]	ξ [dmnl]	ϕ [dmnl]
GAS, UNCONVENTIONAL	1500	10	1990	0.8	4	1.75
WAVE	5	15	2020	0.8	25	18
OTEC	15	10	2040	0.8	25	18

Table 7-3 Parameter values obtained via model calibration and thereafter used for baseline run

Energy Source	URR [EJ] or TP [EJ/yr]	PEAK EROI [dmnl]	INCEPT DATE [yr]	Ξ [dmnl]	ξ [dmnl]	ϕ [dmnl]	R^2
COAL	31500	71	1800	0.904	7.877	6.570	0.97
OIL, CONVENTIONAL	14000	400	1915	0.993	3.570	8.284	0.98
OIL, UNCONVENTIONAL	2500	60	1950	1.000	0.997	0.001	0.85
GAS, CONVENTIONAL	9050	350	1925	0.996	1.409	6.653	0.95
NUCLEAR FISSION	2500	15	1970	1.000	8.271	20.000	0.65
BIOMASS	65	24	1800	0.405	25.000	0.575	0.70
HYDRO	35	60	1904	0.984	0.066	0.000	0.87
GEOTHERMAL	100	10	1980	0.979	0.000	20.000	0.83
TIDAL	1	5	2000	1.000	25.000	1.561	0.33
WIND	175	20	2005	0.800	25.000	18.000	-
SOLAR	750	10	2010	0.800	25.000	18.000	-
ENERGY REQUIREMENT RATIO	1.67						
CAPITAL EFFECTIVENESS	0.0933						

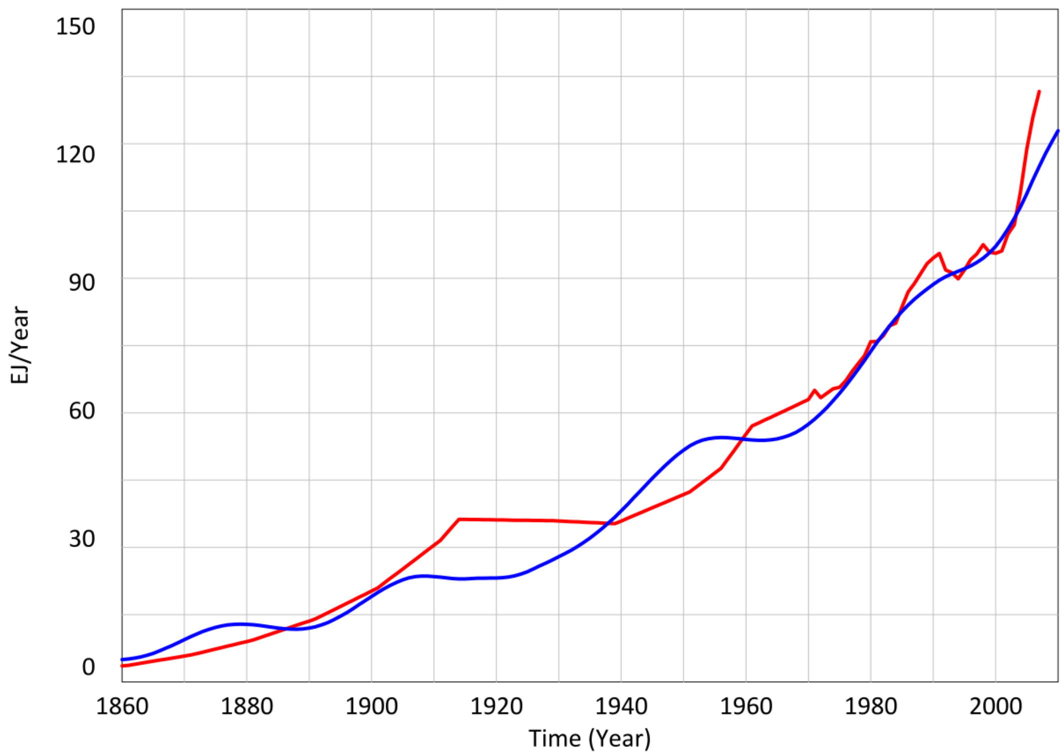


Figure 7-1 Historic coal production (red line) compared with model output for annual COAL PRODUCTION (blue line) from baseline run.

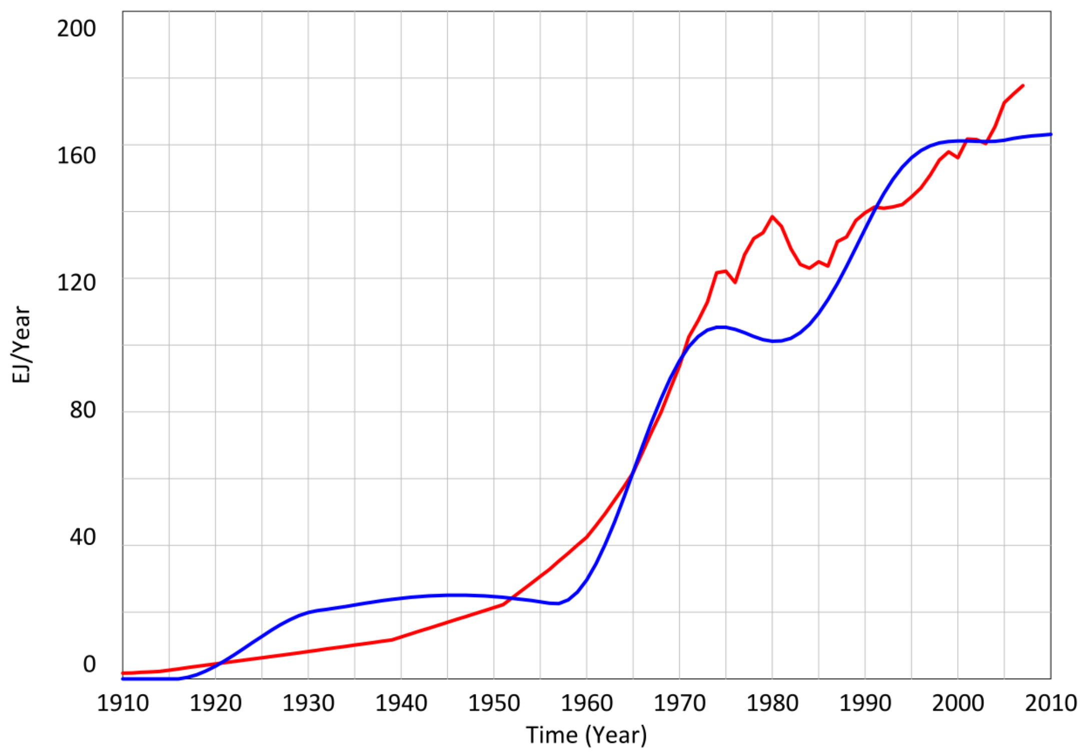


Figure 7-2 Historic conventional oil production (red line) compared with model output for annual CONVENTIONAL OIL PRODUCTION (blue line) from baseline run.
N.B. the difference in vertical scale from coal and conventional gas.

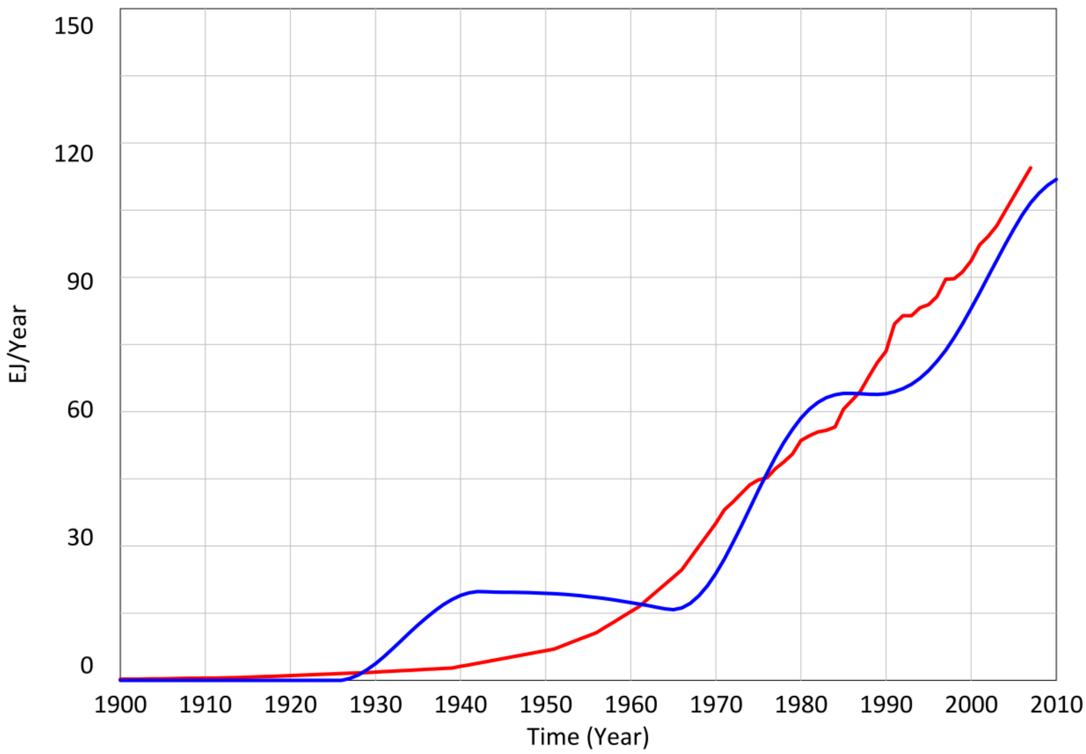


Figure 7-3 Historic conventional gas production (red line) compared with model output for annual CONVENTIONAL GAS PRODUCTION (blue line) from baseline run.

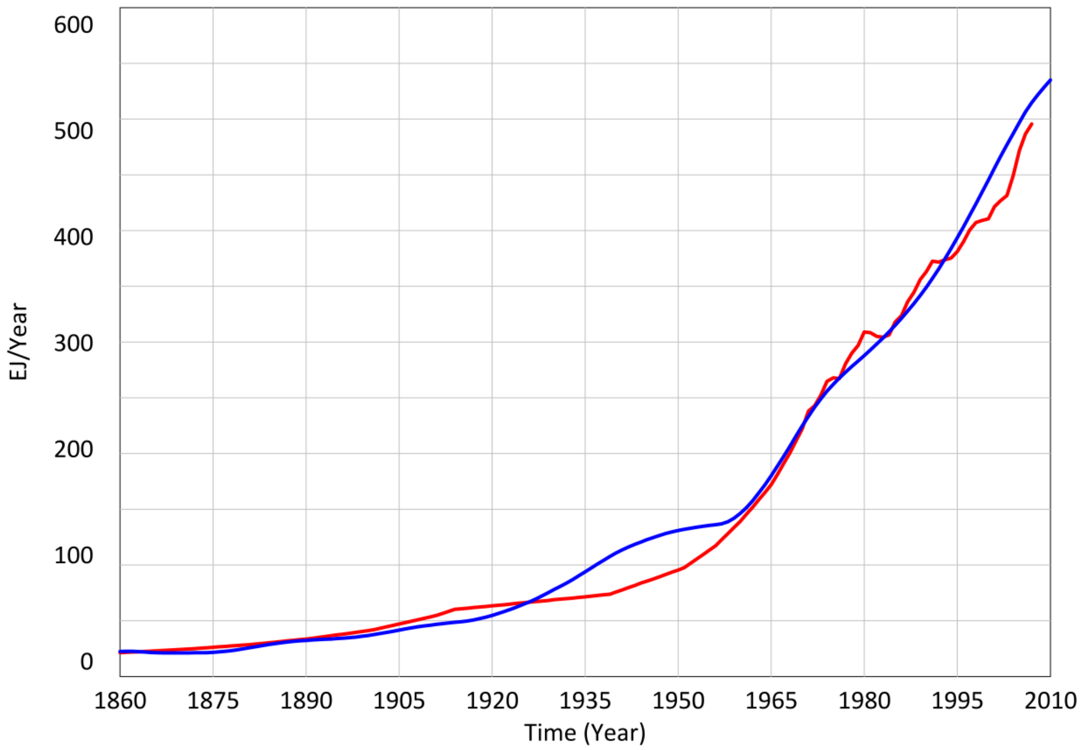


Figure 7-4 Historic total energy production (red line) compared with model output for annual TOTAL ENERGY YIELD (blue line) from baseline run.

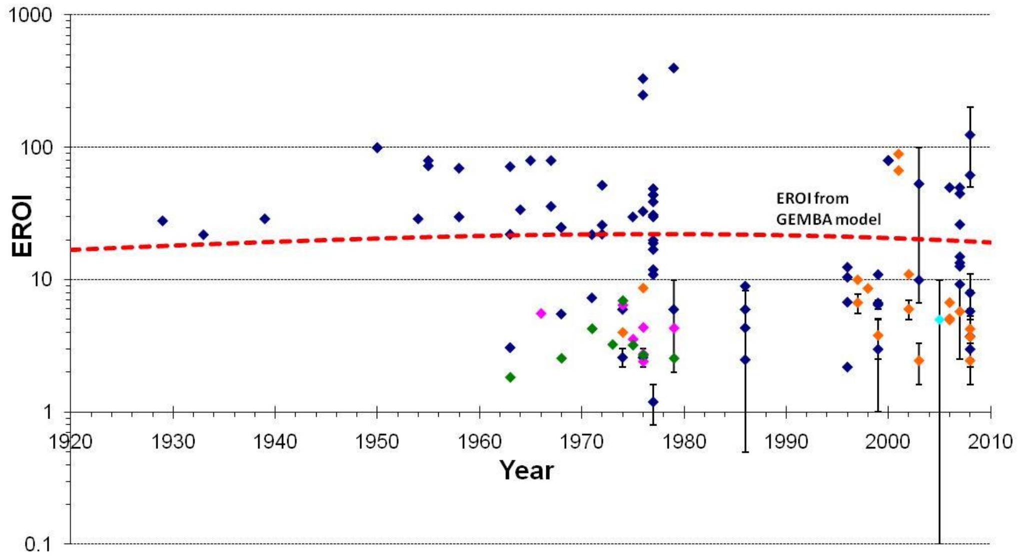


Figure 7-5. Model output $EROI_{COAL}$ of baseline run (red dashed line) in comparison with historical estimates of EROI for coal production (dots).

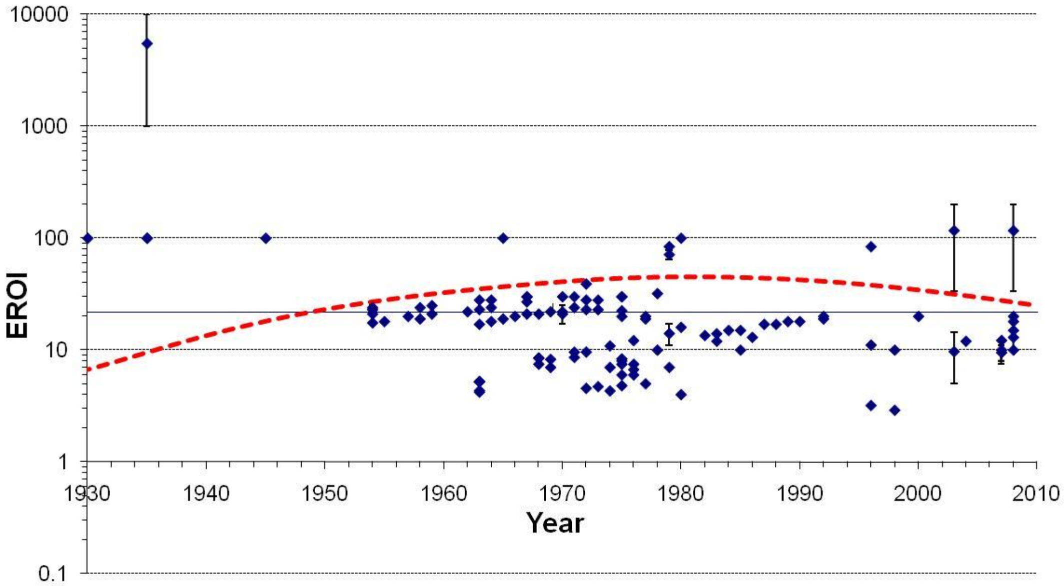


Figure 7-6. Model output $EROI_{OIL, CONVENTIONAL}$ of baseline run (red dashed line) in comparison with historical estimates of EROI for conventional oil production (dots).

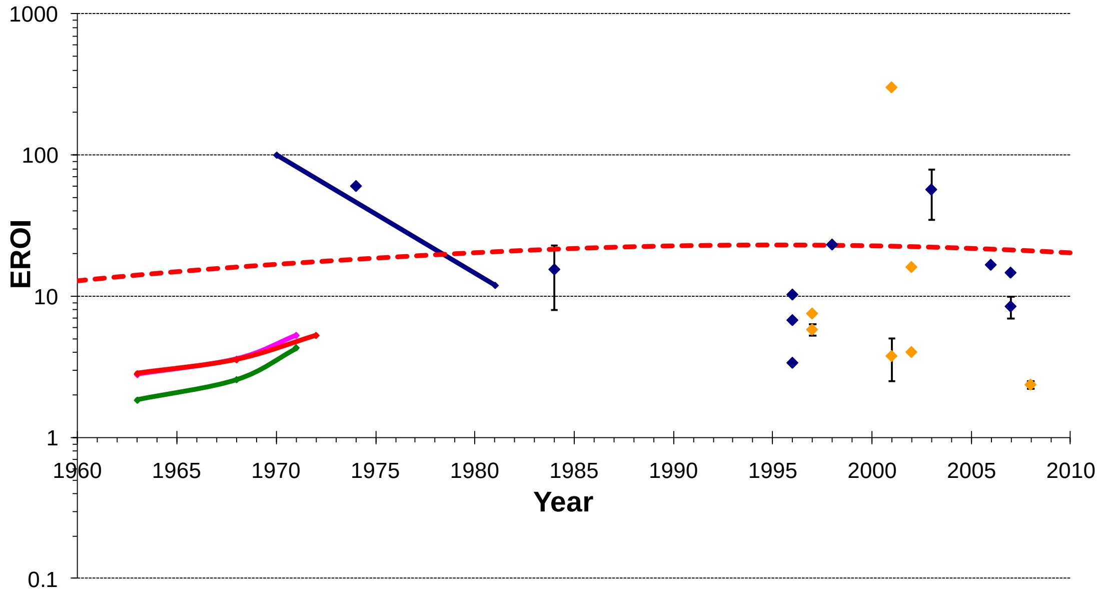


Figure 7-7. Model output $EROI_{GAS,\ CONVENTIONAL}$ of baseline run (red dashed line) in comparison with historical estimates of EROI for conventional gas production (dots).

7.2. Baseline run extrapolated into the future

Within the GEMBA model, there are two key outputs that characterise the state of the model: TOTAL ENERGY YIELD, which represents the total primary energy supply of the global energy system and; NET ENERGY YIELD, which represents the energy available to the main economy after the operating energy and physical capital needs of the energy sector have been met.[37] These model outputs are plotted over the full model time horizon from 1800-2200 in Figure 7-8. TOTAL ENERGY YIELD peaks around 2060 at a value of around 800 EJ/yr and thereafter declines to a value of around 240 EJ/yr in 2200. The model variable NET ENERGY YIELD peaks before TOTAL ENERGY YIELD around 2040 and thereafter declines. This peak is closely linked with the peak in the ENERGY PRODUCTION$_{\text{NON-RENEWABLE}}$ within the model.

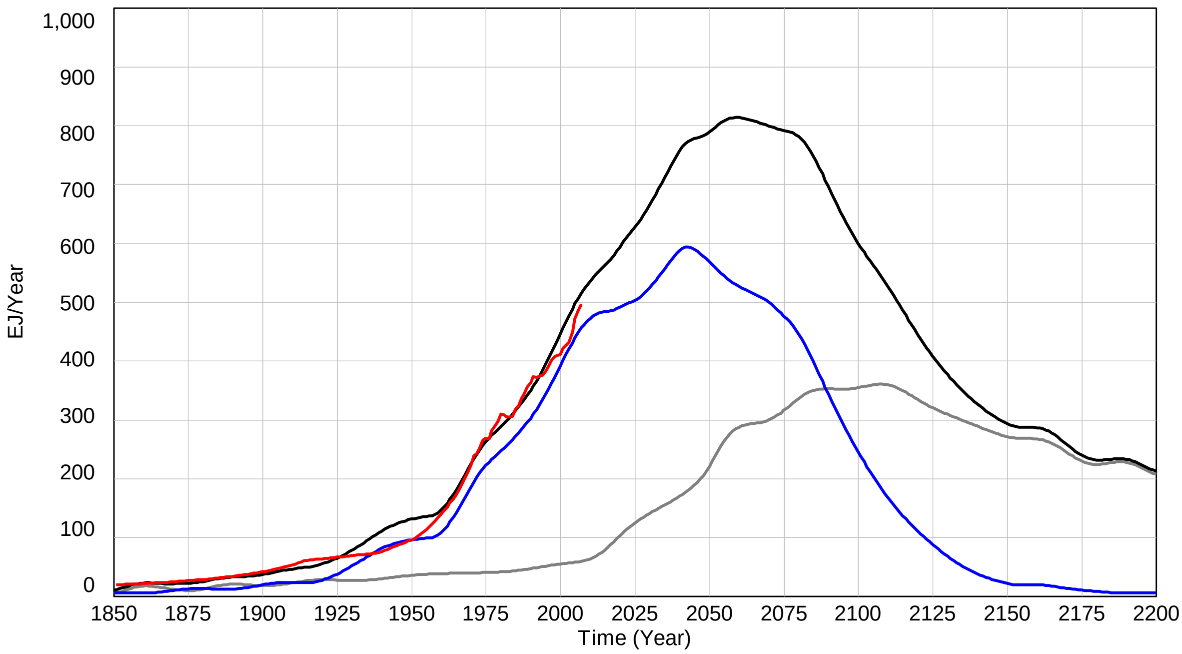


Figure 7-8 Historic data (red line) compared with GEMBA model outputs.
TOTAL ENERGY YIELD (black line), ENERGY PRODUCTION$_{\text{NON-RENEWABLE}}$ (blue line) and ENERGY PRODUCTION$_{\text{RENEWABLE}}$ (grey line) of the baseline run.

The behaviour of the model outputs ENERGY PRODUCTION$_{\text{NON-RENEWABLE}}$ and NET ENERGY YIELD are very strongly linked within the GEMBA model due to the higher CAPITAL FACTOR of renewable energy sources. The decline in ENERGY PRODUCTION$_{\text{NON-RENEWABLE}}$ increases ENERGY DEMAND$_{\text{RENEWABLE}}$. These sources have a higher CAPITAL REQUIREMENT per unit of ENERGY PRODUCTION, meaning there is less INDUSTRIAL OUTPUT available to be re-invested into the

[37] It is assumed within the GEMBA model that these needs take priority over the physical capital needs of the rest of the economy.

main economy. The growth of INDUSTRIAL CAPITAL STOCK slows. TOTAL ENERGY DEMAND is a function of INDUSTRIAL CAPITAL STOCK; therefore TOTAL ENERGY DEMAND also slows.

7.3. Sensitivity to resource parameters

The resource parameters are:

- $\text{URR}_{\text{non-renewable}}$ or $\text{TP}_{\text{renewable}}$
- PEAK EROI_k
- CAPITAL FACTOR_k
- INCEPT DATE_k

The parameter values from the calibration run represent the baseline. In this chapter and hereafter, the term 'net energy yield' is used in the sense used in net energy analysis, i.e. "the amount of energy delivered into the mainstream of economic activity less the amount which is required to bring it there" (N. J. Peet, 1986, p. 16).[38] The purpose of this sensitivity analysis is to gauge the stability of the model outputs TOTAL ENERGY YIELD and NET ENERGY YIELD, after a transition to renewable energy sources has occurred, to changes in the resource parameters both individually, as well as collectively. The following sections present the results of analyses of the sensitivity analysis.

7.3.1. Sensitivity to changes in availability of resources

There is a large uncertainty in the technical potential of all renewable energy sources, as evidenced by the meta-analysis of estimates of potential energy resources (see CHAPTER 6 and Appendix C). To reflect this uncertainty, two scenarios have been modelled: one in which the $\text{TP}_{\text{RENEWABLE}}$ is double the baseline value and one in which $\text{TP}_{\text{RENEWABLE}}$ is half of the baseline value.

The results of the sensitivity analysis are plotted in Figure 7-9 and Figure 7-10. Even if $\text{TP}_{\text{RENEWABLE}}$ is double the baseline value for all renewable sources, TOTAL ENERGY YIELD peaks and declines to a level of 400 EJ/yr. NET ENERGY YIELD also peaks and declines to oscillate around a value of 250 EJ/yr, compared with a value of ~475 EJ/yr in 2010.

[38] This is different to the usage of 'net energy yield' made in CHAPTER 5

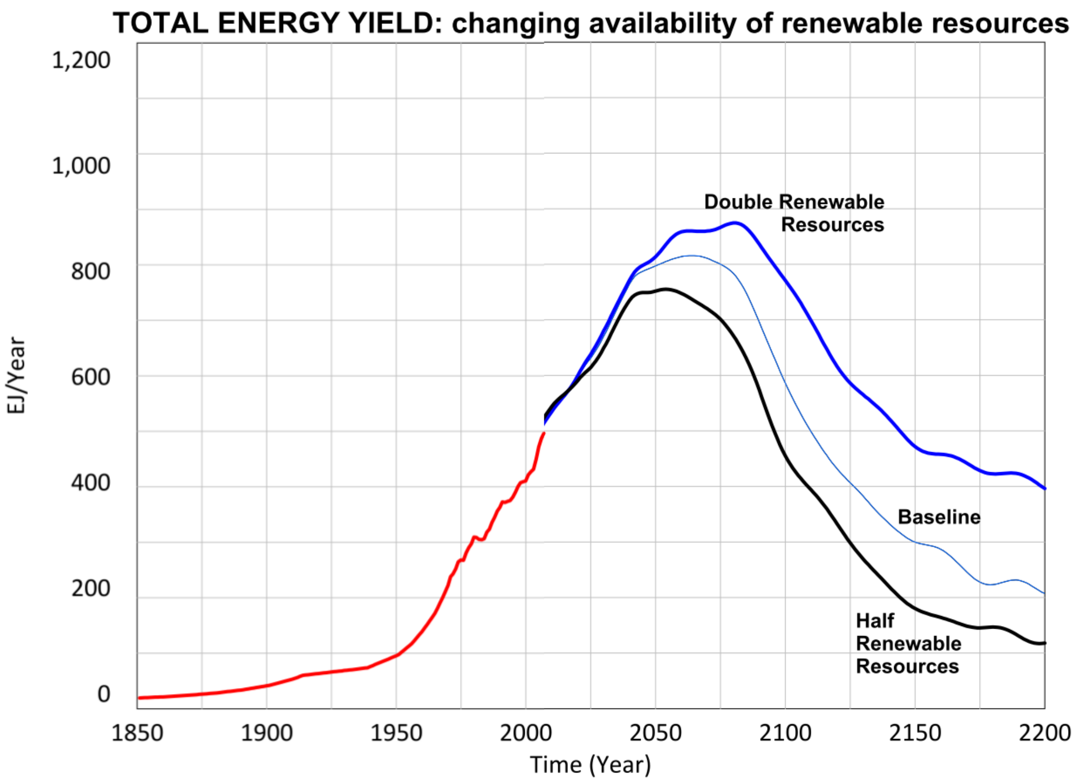


Figure 7-9. Sensitivity analysis of TOTAL ENERGY PRODUCTION to doubling (dark blue line) and halving (black line) $TP_{RENEWABLE}$ from the baseline value, compared with historic total energy production (red line).

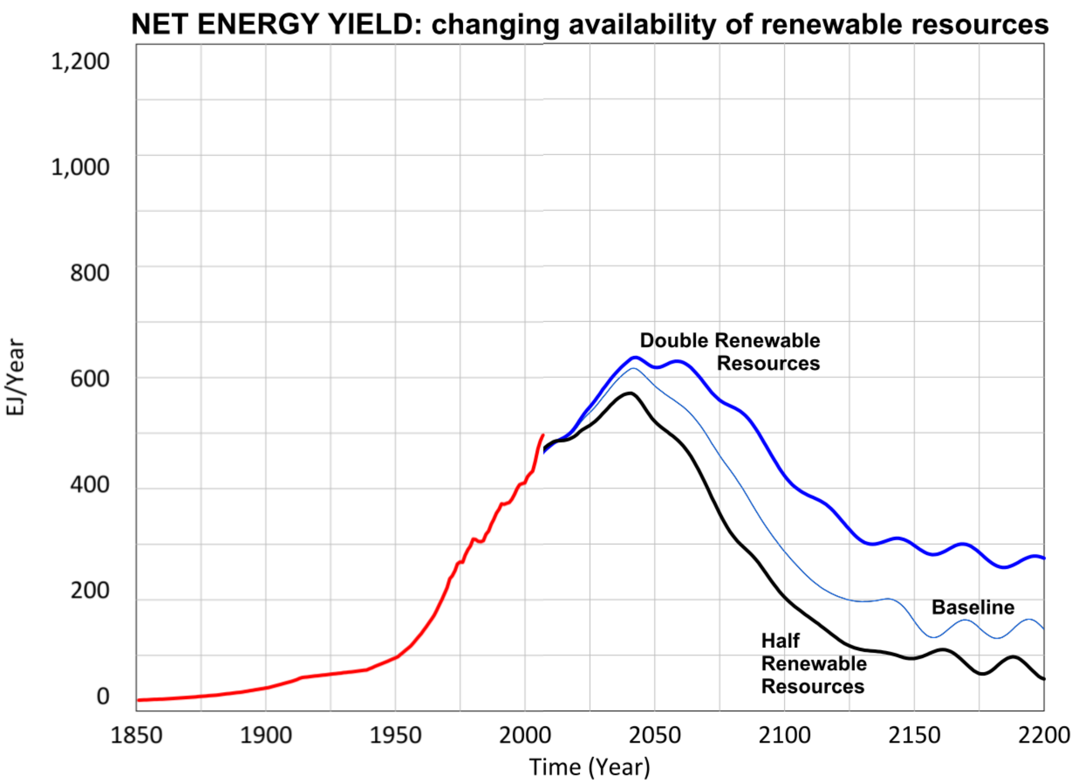


Figure 7-10. Sensitivity analysis of NET ENERGY YIELD to doubling (dark blue line) and halving (black line) $TP_{RENEWABLE}$ from the baseline value, compared with historic total energy production (red line).

7.3.2. Sensitivity to changes in EROI

The EROI of an energy source represents the ratio between the energy gained to the energy that must be invested to produce an energy source. As discussed in CHAPTER 6, fossil fuels have historically had very high values for EROI but are declining as production continues.

The sensitivity of outputs TOTAL ENERGY YIELD and NET ENERGY YIELD to doubling and halving the parameter PEAK $EROI_{RENEWABLE}$ from the baseline value was then analysed to reflect the uncertainty in the EROI of energy sources. The results are displayed in Figure 7-11 and Figure 7-12.

Doubling the parameter PEAK $EROI_{RENEWABLE}$ has the effect of slightly increasing the peak of TOTAL ENERGY YIELD compared with the baseline run. However, despite the doubling in PEAK $EROI_{RENEWABLE}$, TOTAL ENERGY YIELD in 2200 is only 300 EJ/yr compared with a value of 200 EJ/yr in the baseline run. Doubling PEAK $EROI_{RENEWABLE}$ has the effect of raising NET ENERGY YIELD to a value of 220 EJ/yr in 2200, compared with 150 EJ/yr in the baseline case; though still less than half the 2010 value.

Halving PEAK $EROI_{RENEWABLE}$ has the opposite effect. TOTAL ENERGY YIELD peaks at a lower level than in the baseline case and falls to a lower level, as does the NET ENERGY YIELD.

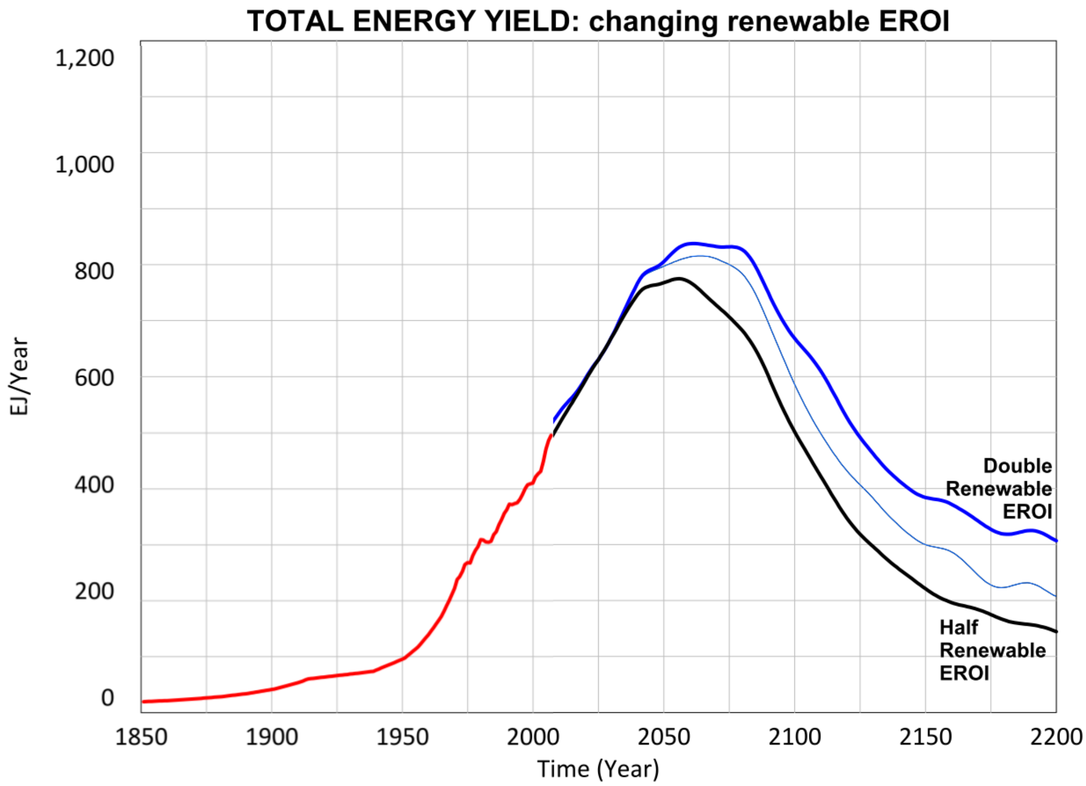


Figure 7-11 Sensitivity analysis of TOTAL ENERGY YIELD to doubling (dark blue line) and halving (black line) $\text{EROI}_{\text{RENEWABLE}}$ from the baseline value, compared with historic total energy production (red line).

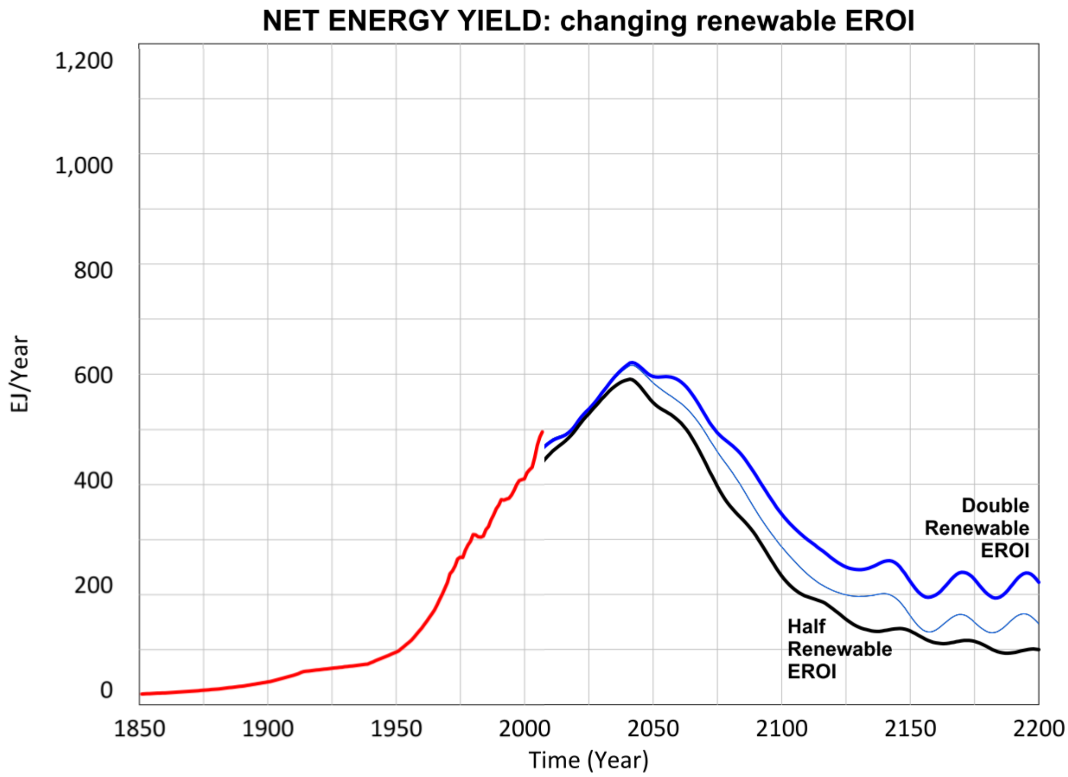


Figure 7-12 Sensitivity analysis of NET ENERGY YIELD to doubling (dark blue line) and halving (black line) $\text{EROI}_{\text{RENEWABLE}}$ from the baseline value, compared with historic total energy production (red line).

7.3.3. Sensitivity to changes in capital intensity

The sensitivity of the TOTAL ENERGY YIELD and the NET ENERGY YIELD to changes in the parameter CAPITAL FACTOR for renewable energy sources was assessed by using a value of 0.45 (half the baseline value) and a value of 0.99. As discussed in CHAPTER 6, the capital factor of most renewable energy sources is, in actuality, closer to 0.99 for most renewable sources. The results are displayed in Figure 7-13 and Figure 7-14.

With a CAPITAL $\text{FACTOR}_{\text{RENEWABLE}}$ of 0.99, the TOTAL ENERGY YIELD and NET ENERGY YIELD closely follow the baseline run.

With a CAPITAL $\text{FACTOR}_{\text{RENEWABLE}}$ of 0.45, the TOTAL ENERGY YIELD increases more quickly than the baseline case, peaking later, at a higher level, and declining to a higher value of around 300 EJ/yr in 2200. The NET ENERGY YIELD also peaks at a higher value than the baseline run, but falls to a fractionally higher level in 2200.

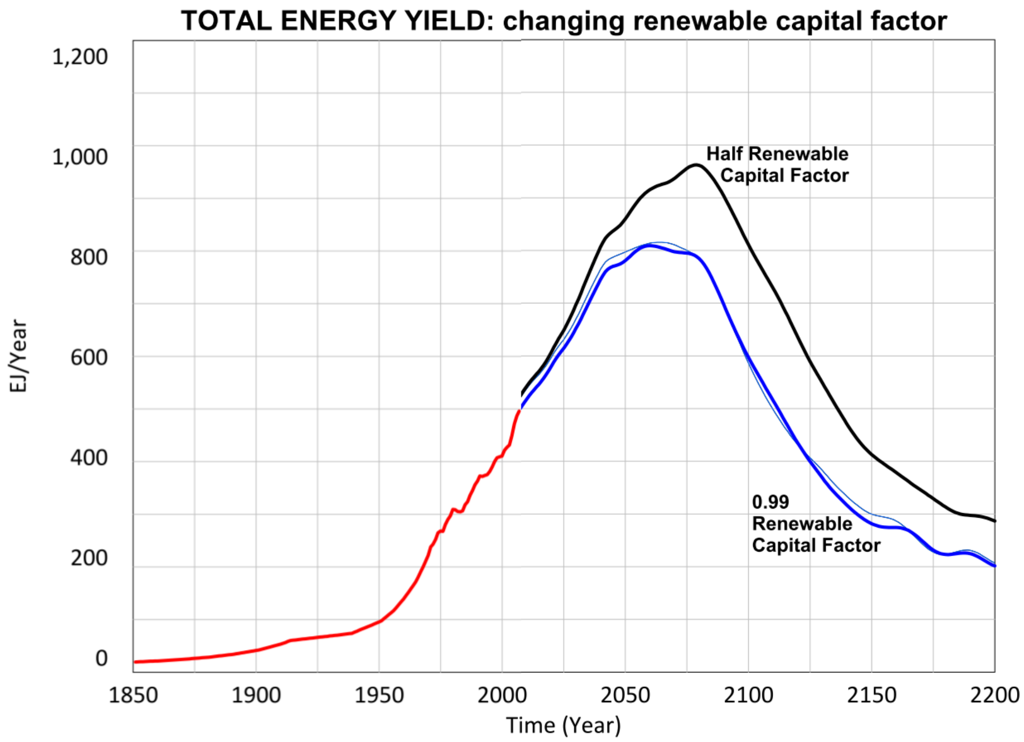


Figure 7-13. Sensitivity analysis of TOTAL ENERGY YIELD to halving (black line) the parameter CAPITAL FACTOR$_{RENEWABLE}$ from the baseline value (pale blue line) and setting CAPITAL FACTOR$_{RENEWABLE}$ = 0.99 (blue line), compared with historic total energy production (red line).

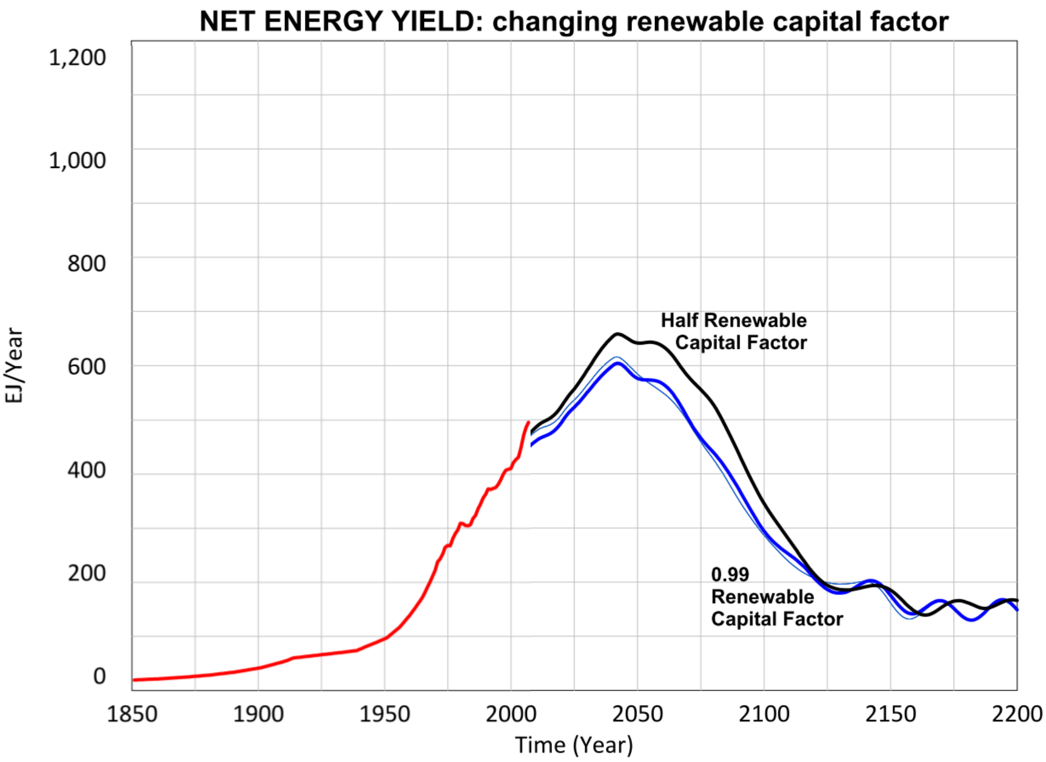


Figure 7-14 Sensitivity analysis of NET ENERGY YIELD to halving (black line) the parameter CAPITAL FACTOR$_{RENEWABLE}$ from the baseline value (pale blue line) and setting CAPITAL FACTOR$_{RENEWABLE}$ = 0.99 (blue line), compared with historic total energy production (red line).

7.3.4. Sensitivity to changes in incept date

The outputs of TOTAL ENERGY YIELD and NET ENERGY YIELD were analysed when adjusting the INCEPT DATES of renewable energy sources. Two scenarios were modelled: one in which the energy sources WAVE and OTEC are available in 2010 and one in which these energy sources are never ready for market deployment (the deployment and non-deployment cases, respectively)[39]. The results are displayed in Figure 7-15 and Figure 7-16.

In the case that WAVE and OTEC are immediately available, the TOTAL ENERGY YIELD peaks later, at a higher level, than in the baseline case before declining to a similar level in 2200. The NET ENERGY YIELD immediately declines after 2010 due to the CAPITAL REQUIREMENTS of setting up the ENERGY CAPITAL $\text{STOCK}_{\text{WAVE, OTEC}}$., before increasing to peak and decline to a similar level as in the baseline case.

In the case that WAVE and OTEC are never deployed, the TOTAL ENERGY YIELD reaches a higher level than both the baseline and the deployment case, but declines to a lower level by 2200. The NET ENERGY YIELD peaks and plateaus later, at a higher level, than the baseline case, before declining to a similar level.

[39] All other ENERGY $\text{SOURCES}_{\text{RENEWABLE}}$ are already available by 2010 in the baseline case

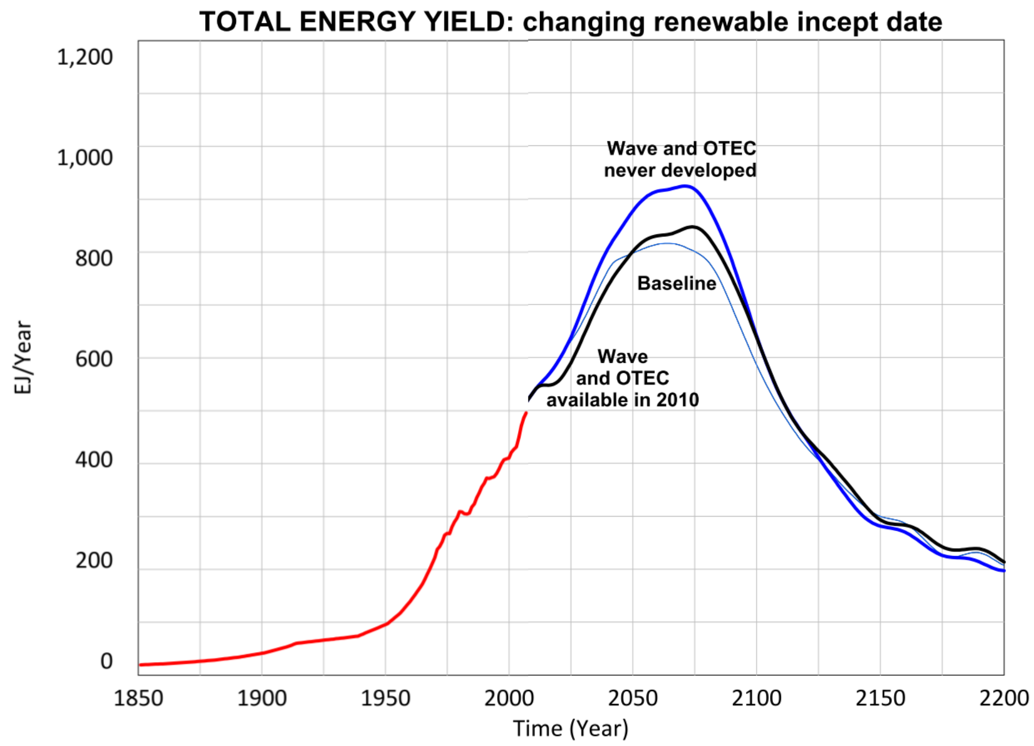


Figure 7-15. Sensitivity analysis of TOTAL ENERGY YIELD to two scenarios: one in which the energy sources WAVE and OTEC are available in 2010 (black line) and one in which these energy sources are never ready for market deployment (blue line) compared with the baseline run (light blue line).
Historic total energy production is in red.

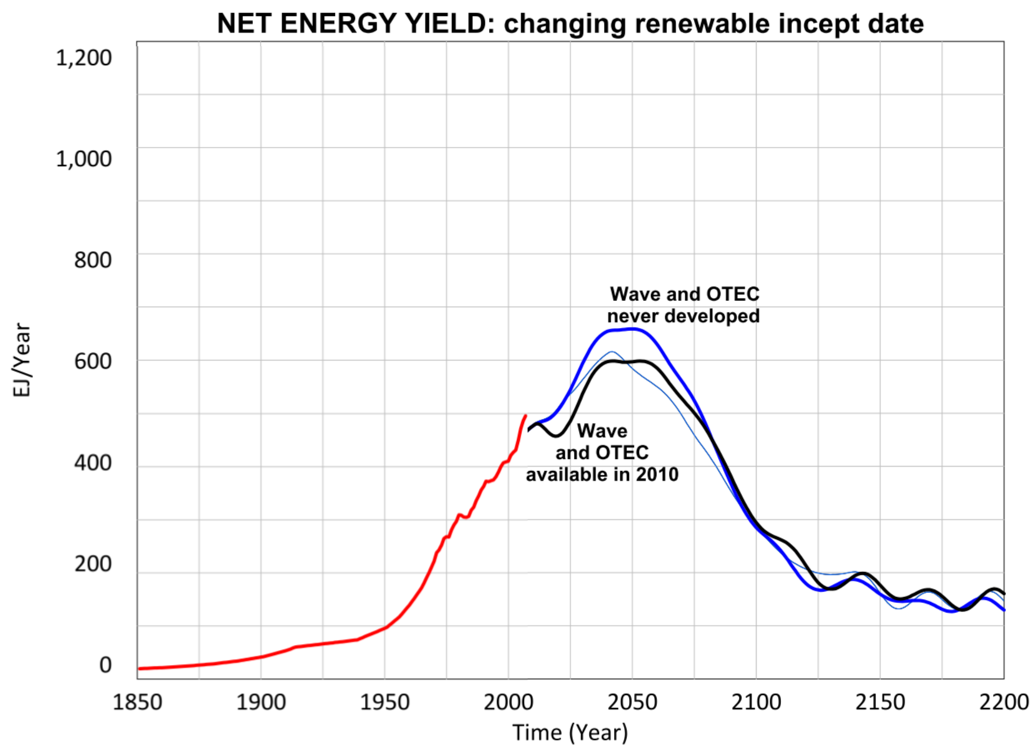


Figure 7-16 Sensitivity analysis of NET ENERGY YIELD to two scenarios: one in which the energy sources WAVE and OTEC are available in 2010 (black line) and one in which these energy sources are never ready for market deployment (blue line) compared with the baseline run (light blue line).
Historic total energy production is in red.

7.3.5. Sensitivity to changes in all resource parameters

The sensitivity of the model outputs TOTAL ENERGY PRODUCTION and NET ENERGY YIELD was then assessed when changing all of the resource parameters simultaneously, to double and half of the baseline value for all ENERGY SOURCES$_{\text{RENEWABLE}}$. These two scenarios represent the most unlikely combination of circumstances and should be treated as highly improbable. The results are shown in Figure 7-17 and Figure 7-18.

In the case of doubling all resource parameters, the TOTAL ENERGY PRODUCTION peaks later, at a slightly higher level, than the baseline case, however declines to a value of 540 EJ/yr in 2200, slightly higher than current TPES. The NET ENERGY YIELD also peaks for longer and declines to a value, 350 EJ/yr, nearly twice the baseline case, but still somewhat below the value in 2010.

In the case of halving all resource parameters, the TOTAL ENERGY PRODUCTION peaks earlier, at a higher level, than the baseline case, before declining to a value around half of around 100 EJ/yr in 2200. The NET ENERGY YIELD declines to a value of around half the baseline value in 2200.

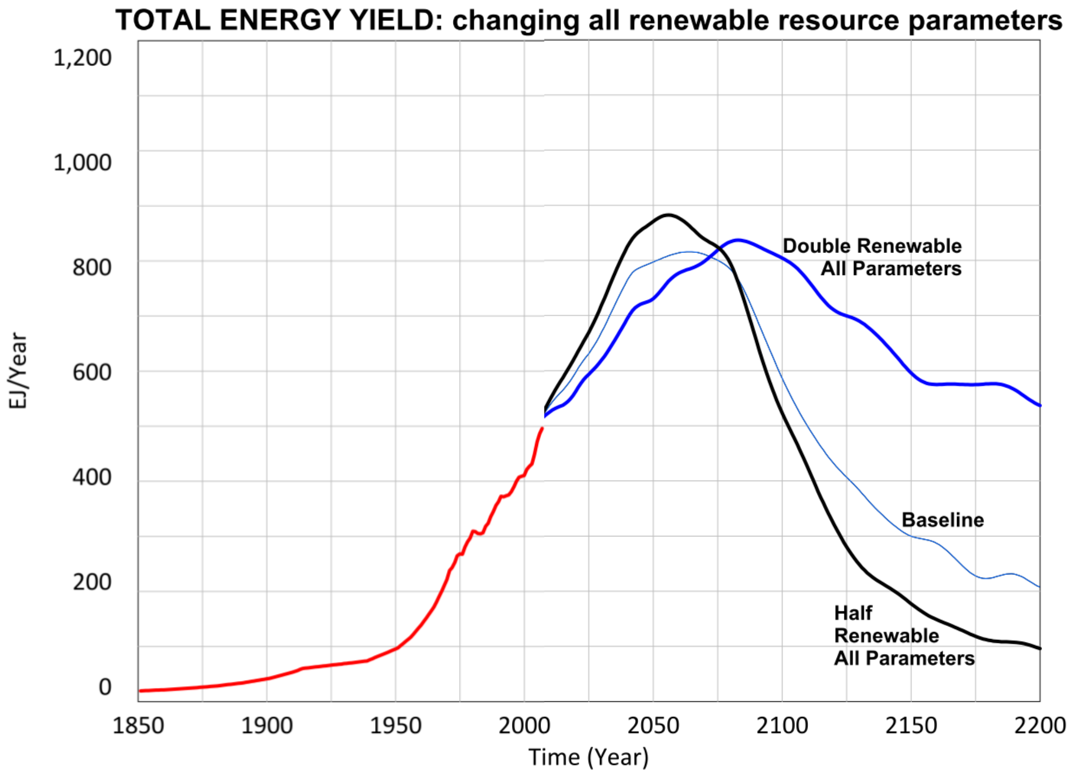


Figure 7-17. Sensitivity analysis of TOTAL ENERGY PRODUCTION to a doubling (blue line) and halving (black line) of all resource parameters for ENERGY SOURCES$_{\text{RENEWABLE}}$ compared with the baseline run (light blue line). Historic total energy production is in red.

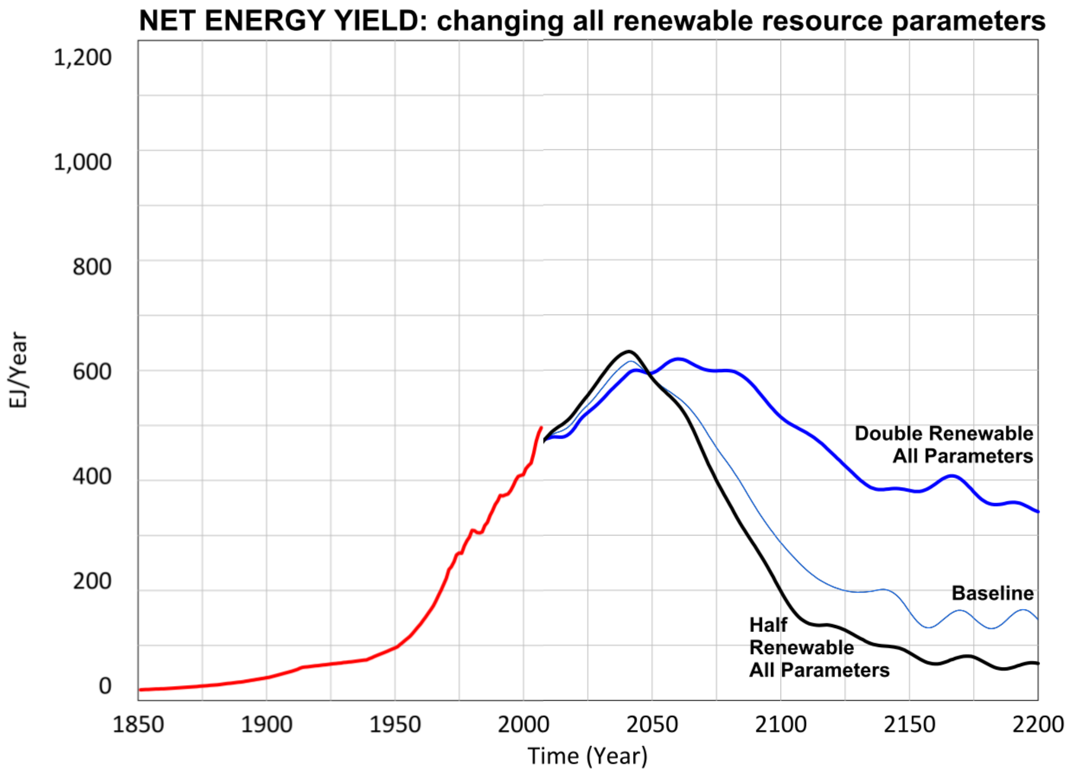


Figure 7-18. Sensitivity analysis of NET ENERGY YIELD to a doubling (blue line) and halving (black line) of all resource parameters for ENERGY SOURCES$_{\text{RENEWABLE}}$ compared with the baseline run (light blue line). Historic total energy production is in red.

7.3.6. TOTAL ENERGY YIELD and NET ENERGY YIELD in 2200

To further assess the sensitivity of the model outputs TOTAL ENERGY PRODUCTION and NET ENERGY YIELD to changes in the resource parameters, the value of both outputs was analysed for the year 2200 in a number of simulations. Histograms were then made of these values, depicted in Figure 7-19 and Figure 7-20

The sensitivity analysis presented here used a Monte Carlo method. 500 model simulations were made wherein the values of the resource parameters were adjusted. The value of the parameter under analysis was picked randomly from a population distributed normally about the baseline value as a mean with standard deviation of 50% of the baseline value. Four analyses were made: four in which each of the four resource parameters was adjusted individually.

The TOTAL ENERGY YIELD of the baseline case in 2200, a value of 207 EJ/yr, is slightly below the mean of all simulations, a value of 249 EJ/yr. The standard deviation of all simulations, a value of 184 EJ/yr, is representative of the large variation in TOTAL ENERGY YIELD in 2200 over all simulations.

Turning to the NET ENERGY YIELD, however, the mean value of all simulations, with a value of 146 EJ/yr, is slightly lower than the baseline value of 152 EJ/yr. The variation across simulations is also lower for the NET ENERGY YIELD, with a standard deviation of 46 EJ/yr.

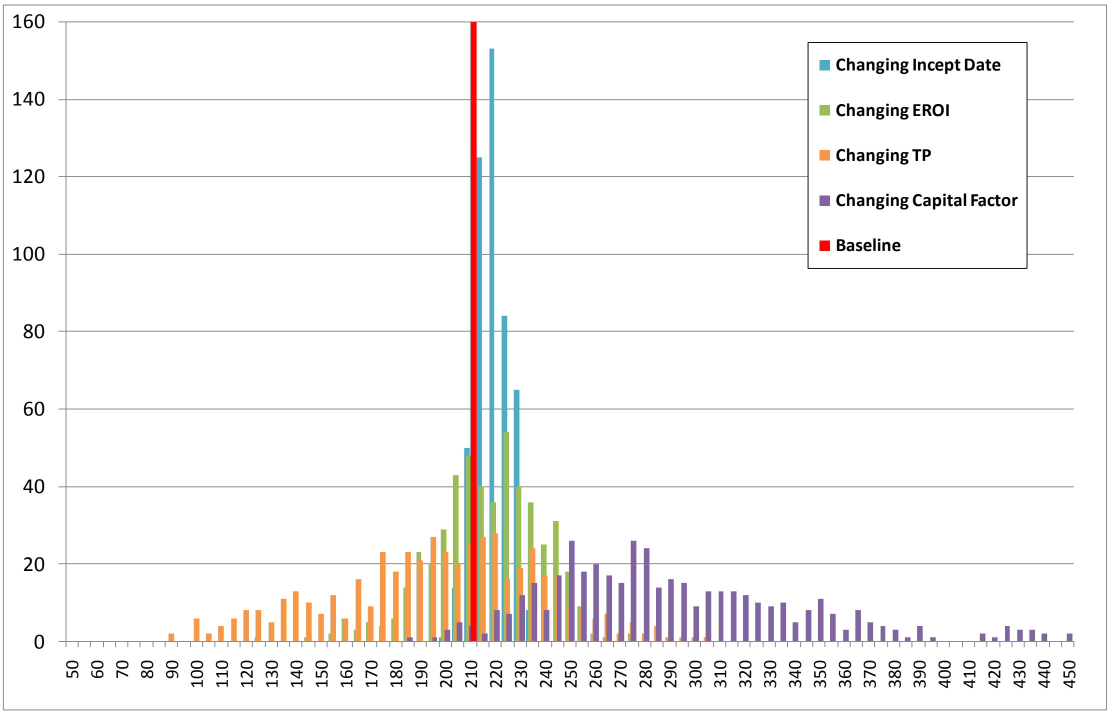


Figure 7-19. Histogram of the values of TOTAL ENERGY YIELD in the model year 2200 in four analyses, adjusting each of the four resource parameters individually.
The value of TOTAL ENERGY YIELD in the baseline run is displayed as a vertical red line.

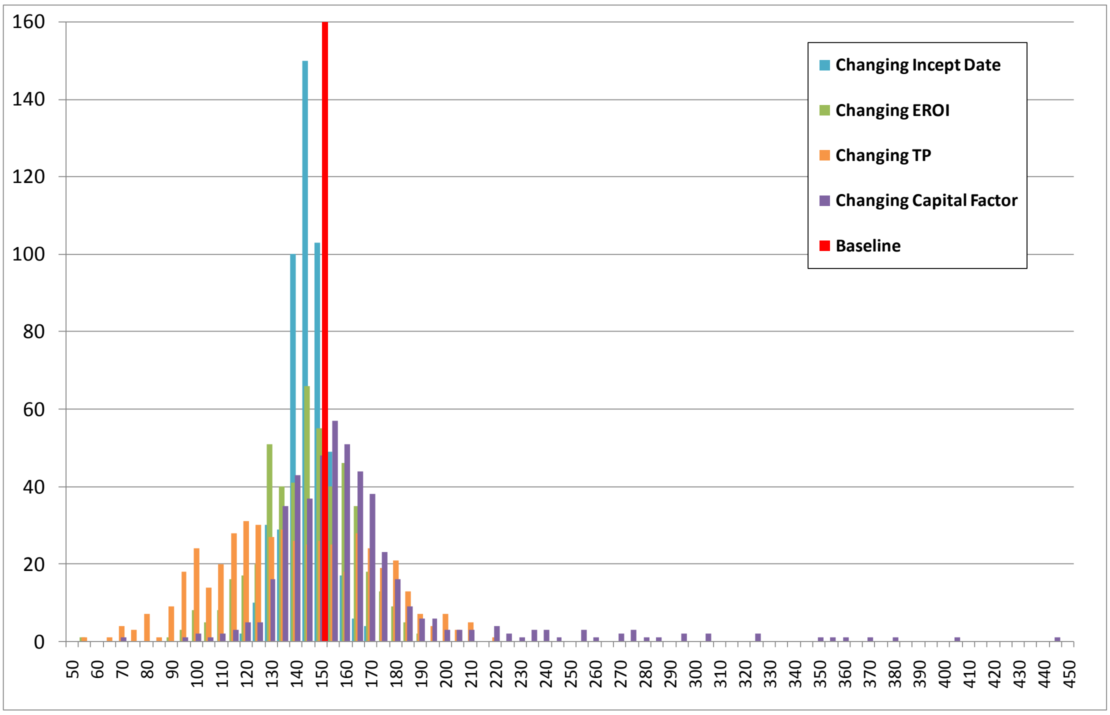


Figure 7-20. Histogram of the values of NET ENERGY YIELD in the model year 2200 in four analyses, adjusting each of the four resource parameters individually.
The value of NET INDUSTRIAL OUTPUT in the baseline run is displayed as a vertical red line.

7.3.7. Summary

The analysis in the preceding sections shows that, under the scenarios that were explored, the most likely outcome is for the TOTAL ENERGY YIELD and NET ENERGY YIELD to decline when a transition to ENERGY SOURCES$_{RENEWABLE}$ is made. The only scenario in which TOTAL ENERGY YIELD is close to the present-day value in 2200 is under a doubling of all of the resource parameters for ENERGY SOURCES$_{RENEWABLE}$. Even in this scenario, NET ENERGY YIELD is still around 25% lower than the present-day value. Since the values of the parameters used in this analysis do not fully reflect the full ranges of the estimates found in CHAPTER 6, an exploration of a larger area of the possibility space is made in the next chapter.

7.4. Further analysis

A further three analyses were made, to test the behaviour of the model outputs total energy yield and net energy yield to changes in $\boldsymbol{P}_{\text{max, RENEWABLE}}$ (which is affected by model parameters $\boldsymbol{\Xi}_{\text{k}}$, ξ_{k} and $\boldsymbol{\phi}_{\text{k}}$) and to changes in the model parameters CAPITAL EFFECTIVENESS and ENERGY REQUIREMENT RATIO, which represent the capital output capacity and energy intensity of the economy, respectively.

7.4.1. Sensitivity to changes in P$_{max}$

The relationship between $\boldsymbol{P}_{\text{max}}$ and the parameters $\boldsymbol{\Xi}_{\text{k}}$, ξ_{k} and $\boldsymbol{\phi}_{\text{k}}$ is discussed in CHAPTER 4. The sensitivity of the TOTAL ENERGY YIELD and the NET ENERGY YIELD to changes in the value of $\boldsymbol{P}_{\text{max, RENEWABLE}}$ was assessed by using a value of 0% and a value of 25%, i.e. that the value of the EROI$_{RENEWABLE}$ is maximised when:

$$\rho_{RENEWABLE} = \frac{ANNUAL\ PRODUCTION_{RENEWABLE}}{TECHNICAL\ POTENTIAL_{RENEWABLE}} = 0 \text{ and } 0.25\text{, respectively.}$$

The results are shown in Figure 7-21 and Figure 7-22.

In both cases the TOTAL ENERGY YIELD peaks at a higher level than the baseline, but declines to a lower value by 2200. The same is true of the NET ENERGY YIELD.

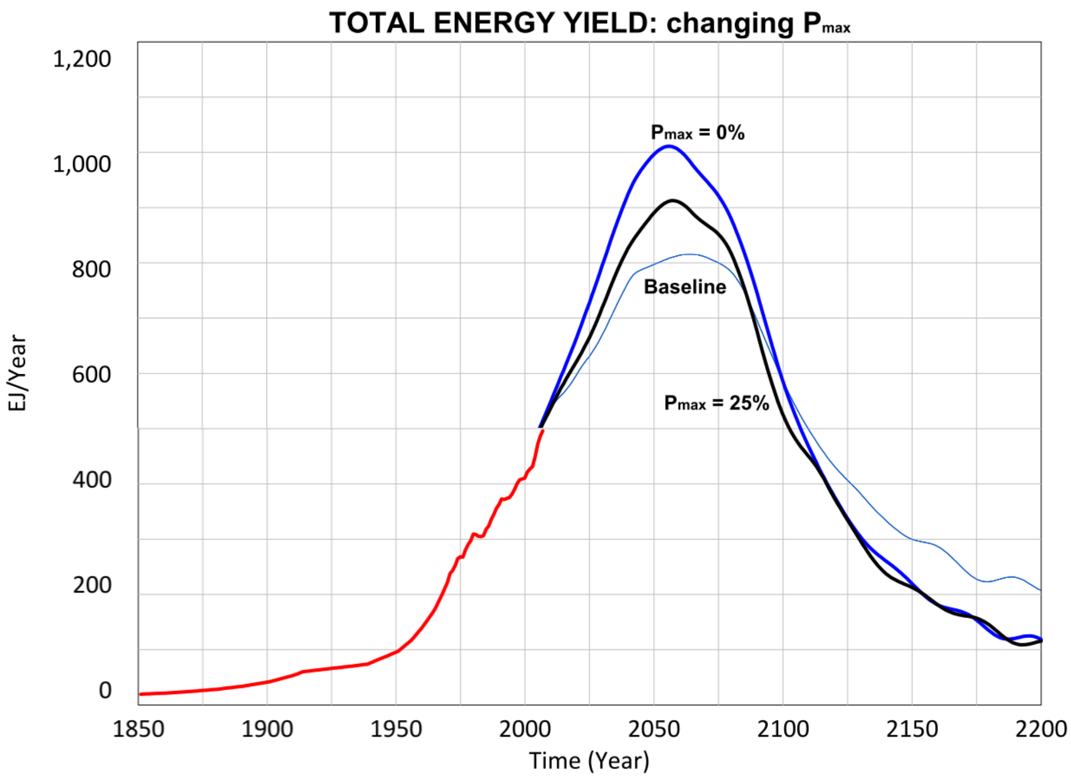


Figure 7-21. Sensitivity analysis of TOTAL ENERGY YIELD to setting $P_{MAX,\ RENEWABLE}$ = 25% (black line) and $P_{MAX,\ RENEWABLE}$ = 0% (blue line) compared with the baseline run (light blue line).
Historic total energy production is in red.

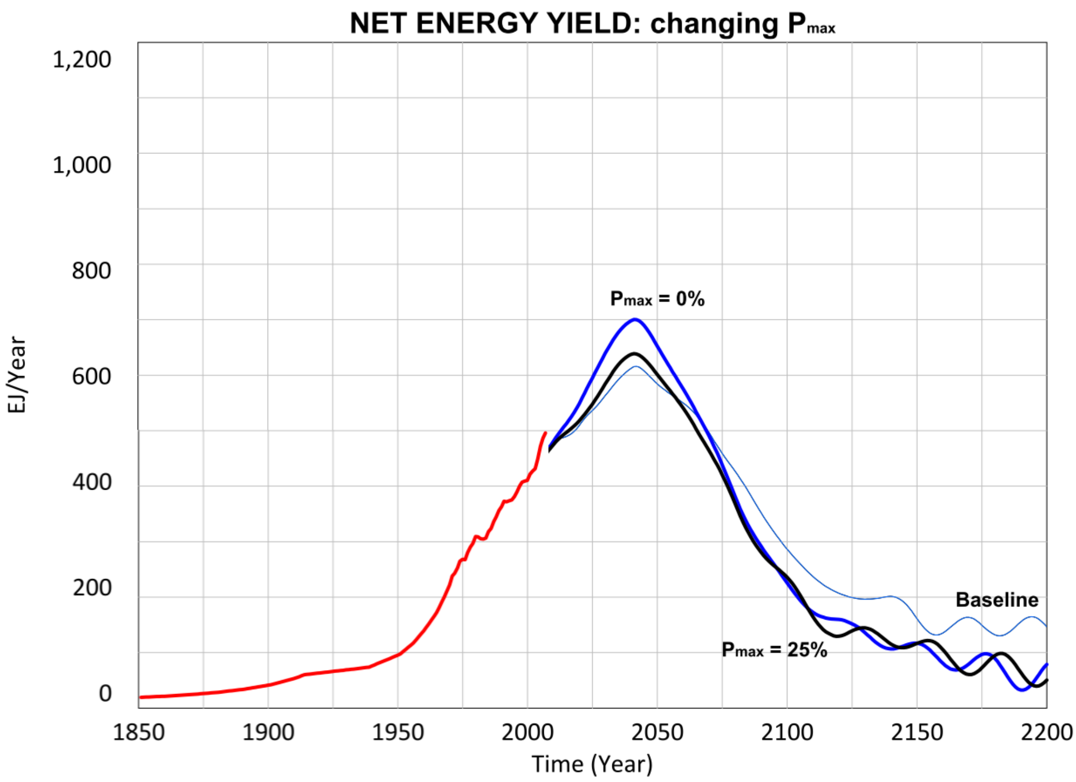


Figure 7-22. Sensitivity analysis of NET ENERGY YIELD to setting $P_{MAX,\ RENEWABLE}$ = 25% (black line) and $P_{MAX,\ RENEWABLE}$ = 0% (blue line) compared with the baseline run (light blue line).
Historic total energy production is in red.

7.4.2. Sensitivity to changes in capital effectiveness

The model parameter capital effectiveness represents the capital output capacity of the economy within the GEMBA model, such that:

$$\text{CAPITAL EFFECTIVENESS}, \kappa = \frac{DESIRED\ INDUSTRIAL\ OUTPUT}{Cap_{ind}}$$

The baseline value of the capital effectiveness is 0.0933; meaning that the capital output capacity is 0.0933 EJ/yr of INDUSTRIAL OUTPUT for each EJ of CAPITAL STOCK$_{\text{INDUSTRIAL}}$.

The sensitivity of the TOTAL ENERGY YIELD and the NET ENERGY YIELD to changes in the value of CAPITAL EFFECTIVENESS was assessed using two scenarios: in the first, CAPITAL EFFECTIVENESS was increased from the baseline value in 2010 to a value of 0.1080 in 2200 as a function of CUMULATIVE CAPITAL STOCK$_{\text{INDUSTRIAL}}$ (a proxy for experience); in the second, the value of CAPITAL EFFECTIVENESS was decreased from the baseline value in 2010 to a value of 0.0791 in 2200, again as a function of CUMULATIVE CAPITAL STOCK$_{\text{INDUSTRIAL}}$. These variations represent a rate of change of ±1×10-5 per EJ of CUMULATIVE CAPITAL STOCK$_{\text{INDUSTRIAL}}$. The results of these scenarios are displayed in Figure 7-23 and Figure 7-24.

In the case of increasing the CAPITAL EFFECTIVENESS, the TOTAL ENERGY YIELD peaks later and at a level of over 100 EJ/yr higher than the baseline case, however declines to a level of within 25 EJ/yr by 2200. The NET ENERGY YIELD follows a similar pattern, though the peak is less pronounced.

Decreasing the CAPITAL EFFECTIVENESS has the opposite effect. Both the TOTAL and NET ENERGY YIELDS peak earlier and at a level lower than the baseline case before declining to a lower level in 2200.

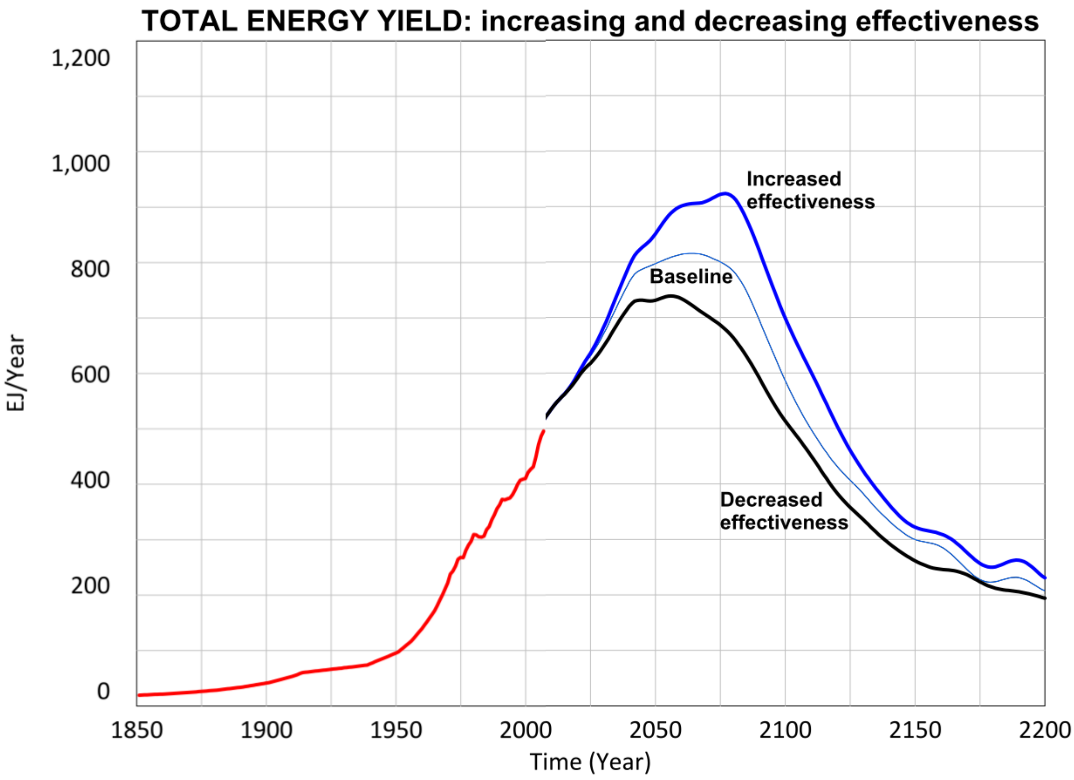


Figure 7-23. Sensitivity analysis of TOTAL ENERGY YIELD to decreasing (black line) and increasing (blue line) CAPITAL EFFECTIVENESS compared with the baseline run (light blue line).
Historic total energy production is in red.

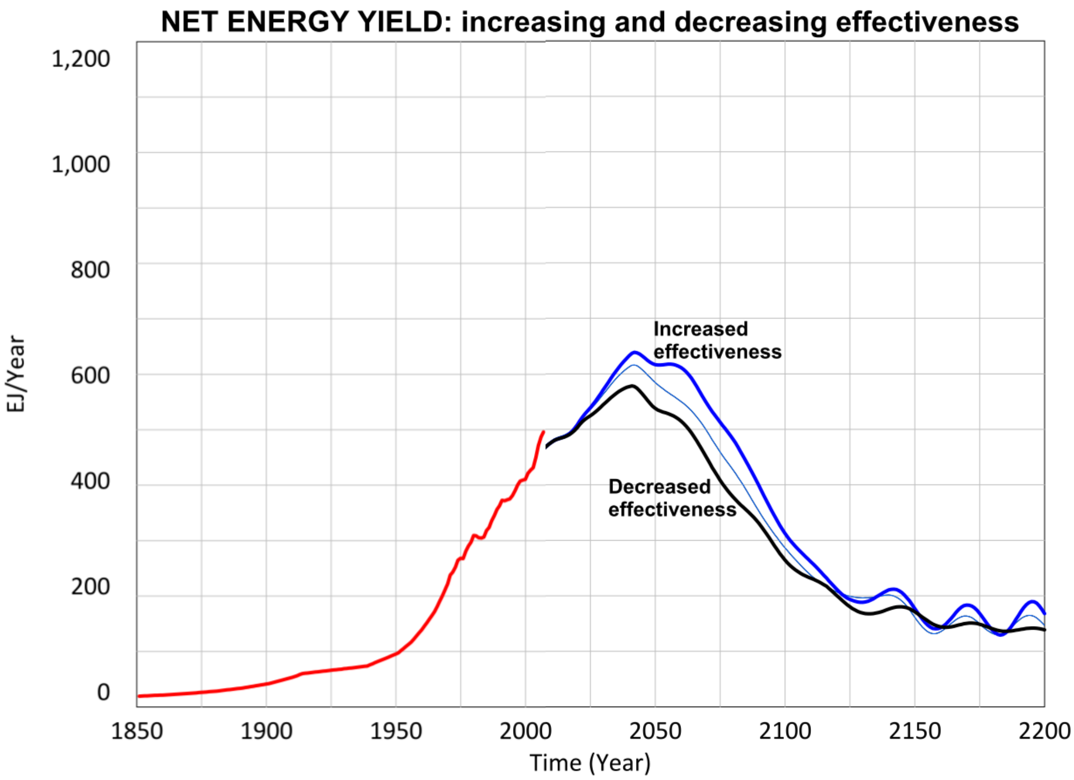


Figure 7-24. Sensitivity analysis of NET ENERGY YIELD to decreasing (black line) and increasing (blue line) CAPITAL EFFECTIVENESS compared with the baseline run (light blue line).
Historic total energy production is in red.

7.4.3. Sensitivity to changes in energy intensity

The sensitivity of the TOTAL ENERGY YIELD and the NET ENERGY YIELD were then analysed, subject to changes in the energy intensity of the economy, represented by the model parameter ENERGY REQUIREMENT RATIO. The baseline value of this parameter is 1.67 meaning that the proportion of the NET ENERGY YIELD that is embodied as INDUSTRIAL OUTPUT is 1/1.67 = 0.60[40]. In these scenarios, it is assumed that, from the present day, a greater or lesser proportion of the NET ENERGY YIELD is diverted into INDUSTRIAL OUTPUT, the proportion changing as a function of CUMULATIVE INDUSTRIAL OUTPUT to a value of 2.111 (increasing) or 1.008 (decreasing) in 2200, from baseline value of 1.67. The effects on the TOTAL ENERGY YIELD and the NET ENERGY YIELD are displayed in Figure 7-25 and Figure 7-26.

Increasing the ENERGY REQUIREMENT RATIO causes the TOTAL ENERGY YIELD to peak at a higher level than the baseline case, however by 2200 the TOTAL ENERGY YIELD has declined to a value lower than the baseline. A similar effect is seen for the NET ENERGY YIELD.

Increasing the ENERGY REQUIREMENT RATIO has the opposite effect of decreasing the peak, but increasing the long term output of both TOTAL and NET ENERGY YIELDS.

[40] In all likelihood, this value is too large, since the industrial sector consumed only 26% of TPES in 2006 (IEA 2008).

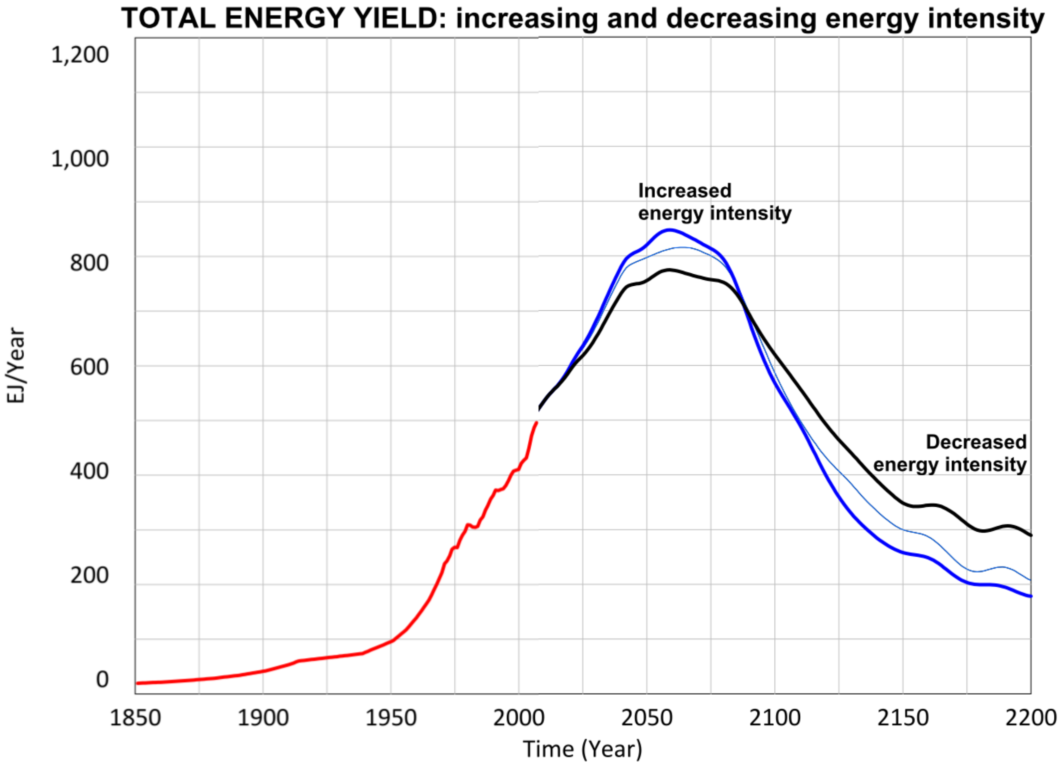


Figure 7-25. Sensitivity analysis of TOTAL ENERGY YIELD to decreasing (black line) and increasing (blue line) model parameter ENERGY REQUIREMENT RATIO compared with the baseline run (light blue line).
Historic total energy production is in red.

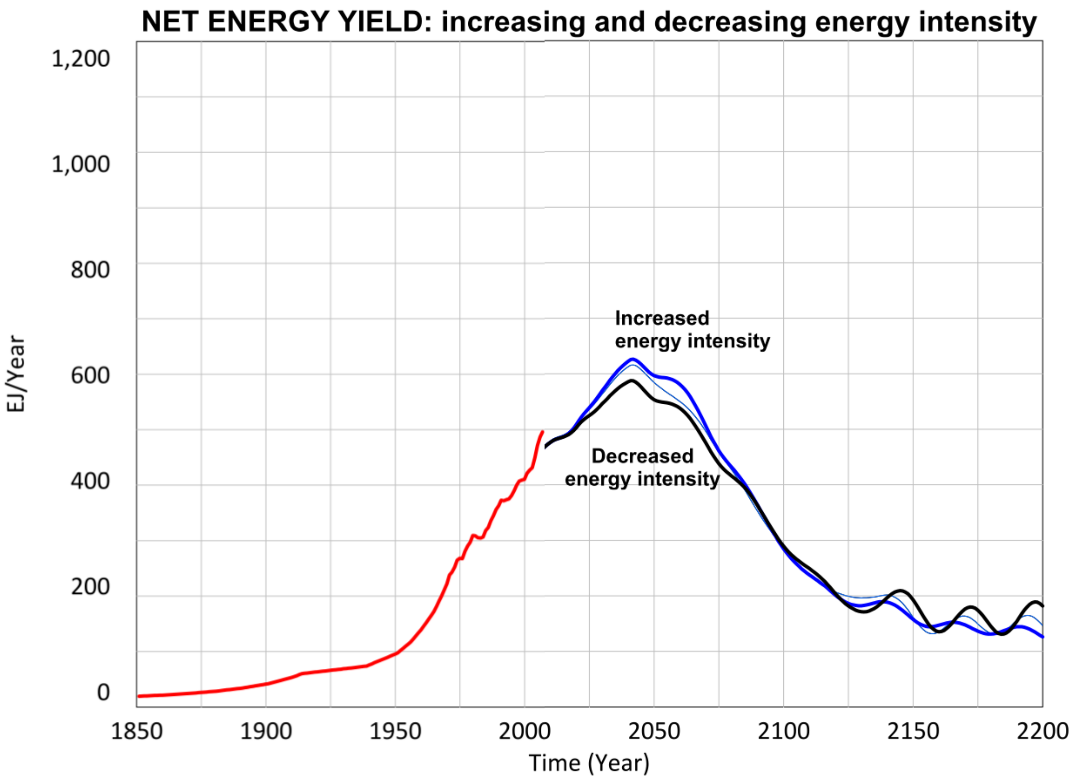


Figure 7-26. Sensitivity analysis of NET ENERGY YIELD to decreasing (black line) and increasing (blue line) model parameter ENERGY REQUIREMENT RATIO compared with the baseline run (light blue line).
Historic total energy production is in red.

CHAPTER 8. EXPLORING MORE OF THE POSSIBILITY SPACE

In this chapter, a greater portion of the possibility space will be mapped using the GEMBA model. From the meta-analyses in CHAPTER 6, the range of estimates for EROI and total amount of resources was sometimes two orders of magnitude, for some of the energy sources. The analyses in this chapter will be done in three ways: firstly, a case-study will be made of SOLAR energy[41] exploring the relationship between PEAK EROI and TECHNICAL POTENTIAL for this energy source; secondly, a scenario-type approach will attempt to define the edges of the possibility space and their implications for TOTAL ENERGY YIELD and; thirdly, a Monte Carlo simulation will range over the majority of that space and give a statistical interpretation of it's landscape.

8.1. Solar energy – a case study

This section will look at the role that solar energy can play in affecting the GEMBA output TOTAL ENERGY YIELD. The solar energy resource is an unknown element in that the potential resource base is enormous. Estimates of the technical potential range over four orders of magnitude. The availability of solar energy is certainly not in doubt. What is questionable is the EROI, estimates of which range from less than 1 to over 70, and the delivery of material resources necessary to capture the available solar flux. Despite studies exploring the future potential of reductions in the energy payback time (EPBT) for solar PV (Alsema et al.2006), there is no clear physical limit to the EROI of solar devices in the very long term. To explore this issue in more detail, the method of analysis used in this section will be to measure the GEMBA output TOTAL ENERGY YIELD in the year 2200, to changes in the model parameters

[41] Solar was chosen since this resource exhibits the largest estimates of TP (up to 86,000 EJ/yr) and, as such could be considered a 'wild card'.

PEAK $EROI_{SOLAR}$ and TP_{SOLAR}, all other parameters being kept at their baseline values. This will enable the definition of the topographical landscape of TOTAL ENERGY YIELD in the PEAK $EROI_{SOLAR}$ vs. TP_{SOLAR} space to determine what combination of these parameters would allow the energy system to deliver a certain level of TOTAL ENERGY YIELD.

Looking at Figure 8-1, it can be seen that the baseline values of PEAK $EROI_{SOLAR}$ = 10 and TP_{SOLAR} = 750 EJ/yr represent a very low point in the TOTAL ENERGY YIELD landscape. Assuming a PEAK $EROI_{SOLAR}$ of 100 and a TP_{SOLAR} of 5000 EJ/yr allows the TOTAL ENERGY YIELD to reach over 3500 EJ/yr in 2200. A TP_{SOLAR} of 5000 EJ/yr represents the 83 percentile of estimates of the technical potential of the solar resource. The median values of estimates of EROI for solar are 7, 5 and 11 for PV, STEC and solar thermal, respectively. The mean values are 9, 11 and 6, respectively. Assuming that these represent half of what is technically achievable, the TOTAL ENERGY YIELD is limited to below 2000 EJ/yr. Assuming that the PEAK $EROI_{SOLAR}$ is 30 means that the TP_{SOLAR} must be 1000 EJ/yr to achieve a total energy yield greater than current levels of TPES.

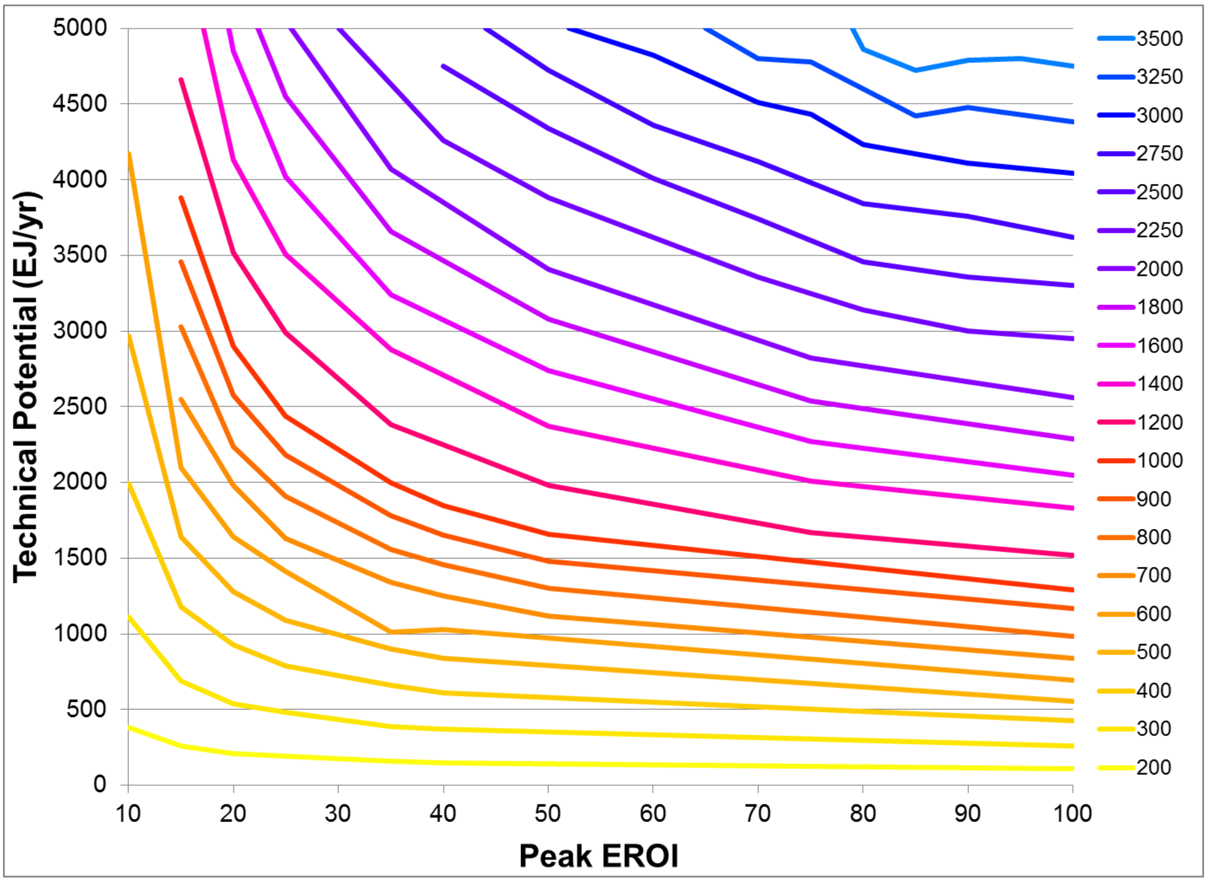


Figure 8-1. Plot of TP_{SOLAR} vs. PEAK $EROI_{SOLAR}$ contours of TOTAL ENERGY YIELD.

8.2. Mapping the corners of the possibility space

The extremes of the possibility space will be pinpointed by setting the parameter values PEAK $\text{EROI}_{\text{RENEWABLE}}$ and $\text{TP}_{\text{RENEWABLE}}$ to the maximum and minimum values found in the meta-analysis (see CHAPTER 6). These runs will produce the upper and lower (respectively) bounds for the model output TOTAL ENERGY YIELD. The results of the two runs are plotted in Figure 8-2.

The upper bound on the TOTAL ENERGY YIELD from all ENERGY $\text{SOURCES}_{\text{RENEWABLE}}$ is 3294 EJ/yr in 2200[42]. The lower bound is 112 EJ/yr. Obviously, this range gives a lot of scope for possible futures of the energy-economy system. The upper bound represents essentially a business as usual continuation of the development of the last 200 years of an approximate 1-2% per year increase in TPES. The lower bound represents decline of TPES back to the levels of the 1950's.

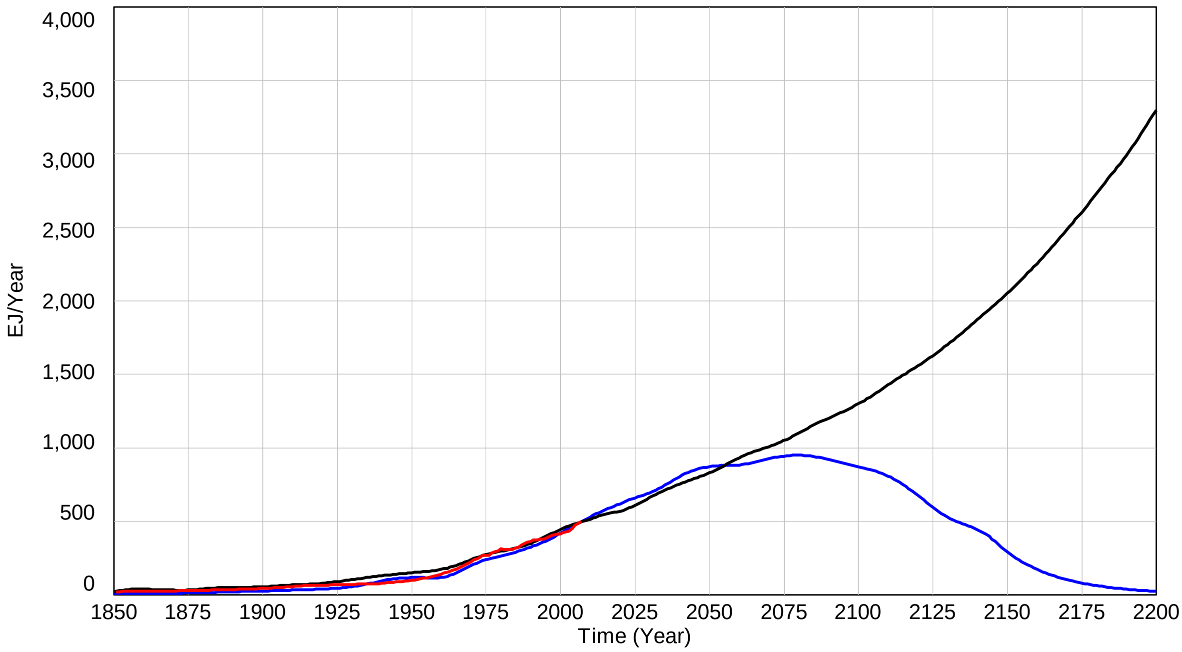


Figure 8-2. GEMBA output TOTAL ENERGY YIELD from runs upper (black line) and lower (blue line) bounds. Historical TPES (red line) is shown for comparison.

8.3. Mapping the landscape of the possibility space

The method used for this analysis is a Monte Carlo simulation, wherein 1000 simulations of the GEMBA model are run using varying parameter values. The values for the parameters PEAK $\text{EROI}_{\text{RENEWABLE}}$ and $\text{TP}_{\text{RENEWABLE}}$ (other than SOLAR) were drawn randomly from a beta

[42] It should be noted, however, that the TOTAL ENERGY YIELD is still increasing at this point and so may not stabilise until a much higher value is reached.

distribution based on the estimates from the meta analyses from CHAPTER 6. The beta distribution is parameterised by two positive shape parameters, which are normally labelled α and β. The values of these parameters were obtained by least squares fitting with the distribution of estimates for the EROI and TP for each of the energy sources. TP_{SOLAR} was modelled using a uniform distribution of 8000 EJ/yr

The distribution across all 1000 simulations of the GEMBA output TOTAL ENERGY YIELD for the year 2200 is shown as a histogram in Figure 8-3 and as a cumalitive frequency plot in Figure 8-4. The mean value of the TOTAL ENERGY YIELD in 2200 was 785 EJ/yr. The 25, 50 (median), 75 and 95 percentiles (indicated with dashed red lines) were 592 EJ/yr, 756 EJ/yr, 952 EJ/yr and 1281 EJ/yr, respectively.

The analysis was repeated using a uniform distribution of 4000 and 12,000 EJ/yr for TP_{SOLAR}. The results are plotted in Figure 8-5. The mean, median and 5, 25, 75 and 95 percentile values are shown in .

Table 8-1. Mean, median and percentile values from Monte Carlo analyses, using different values for TP_{SOLAR}. All values are in EJ/yr.

Solar TP (EJ/yr)	Low 4000	Med 8000	Hi 12000
Mean	639	785	840
Median	617	756	797
5%	331	403	379
25%	480	592	607
75%	774	952	1042
95%	1009	1281	1429

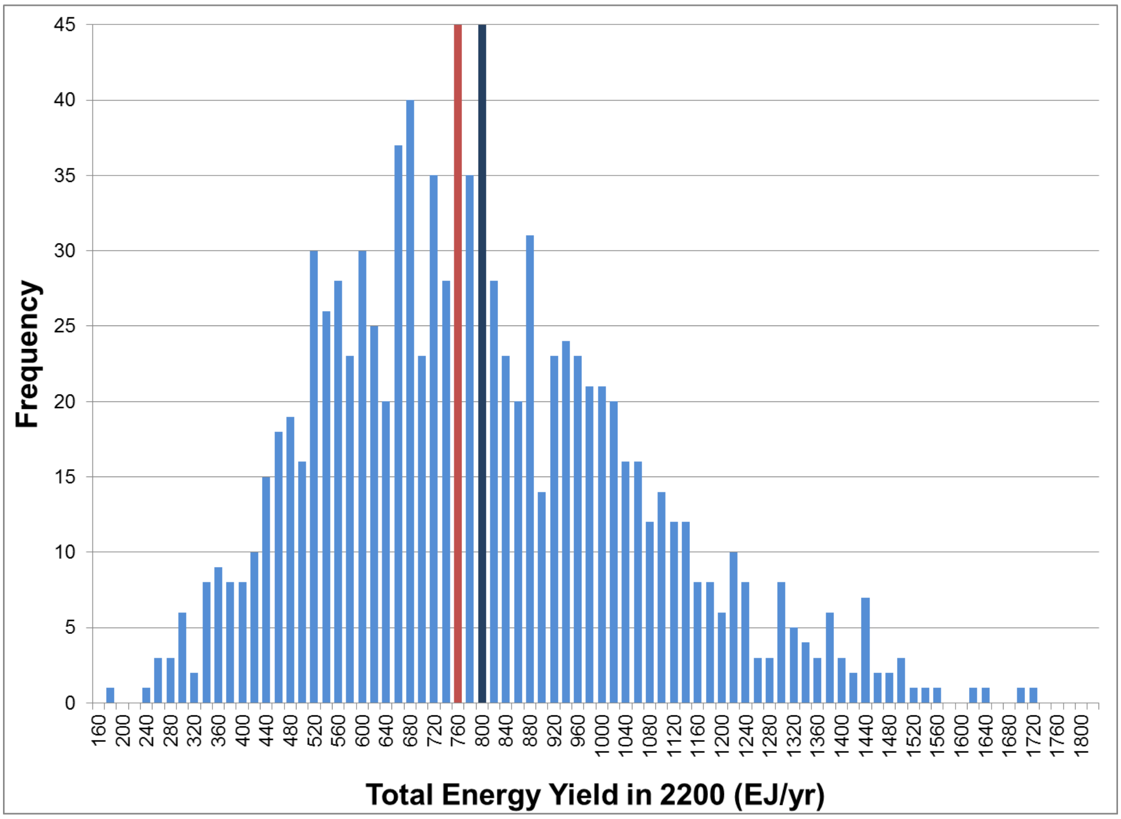


Figure 8-3. Histogram of values from Monte Carlo simulation for GEMBA output total energy yield in 2200. The mean of all runs (dark blue line) is 785 EJ/yr, the median value (red line) is 756 EJ/yr.

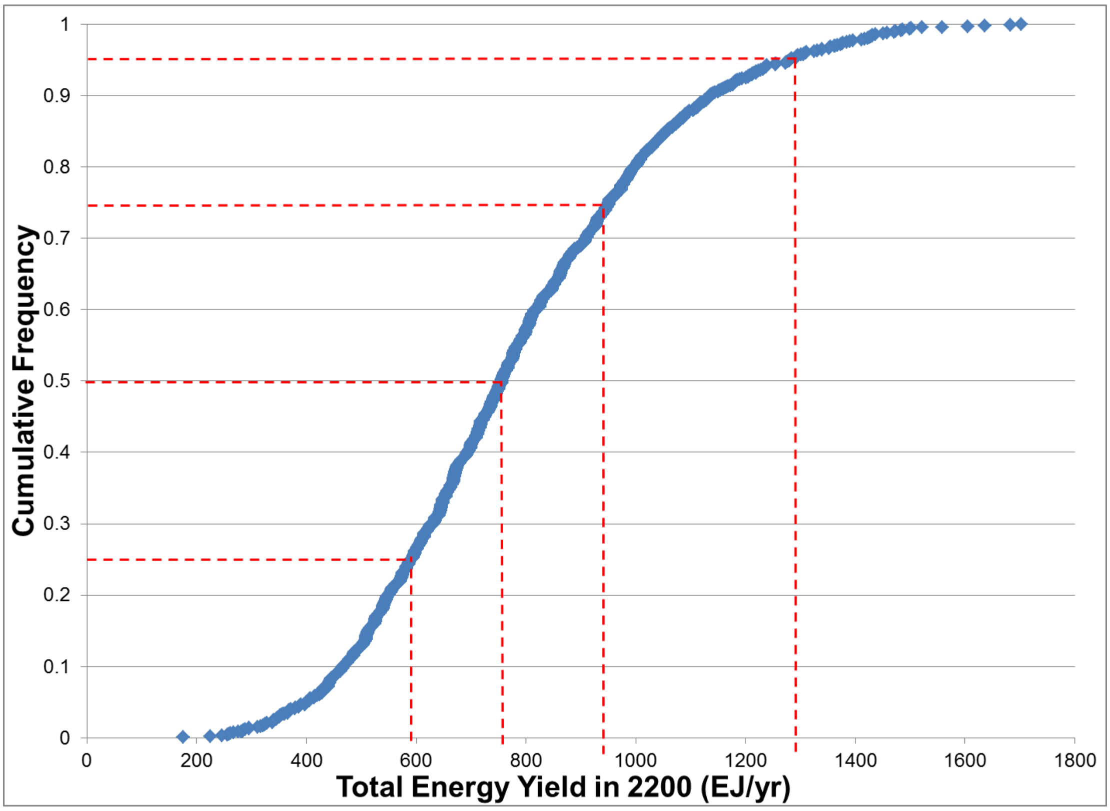


Figure 8-4. Cumulative frequency of values from Monte Carlo simulation for GEMBA output TOTAL ENERGY YIELD in 2200.
Percentiles 25, 50 (median), 75 and 95 are marked with red dashed lines.

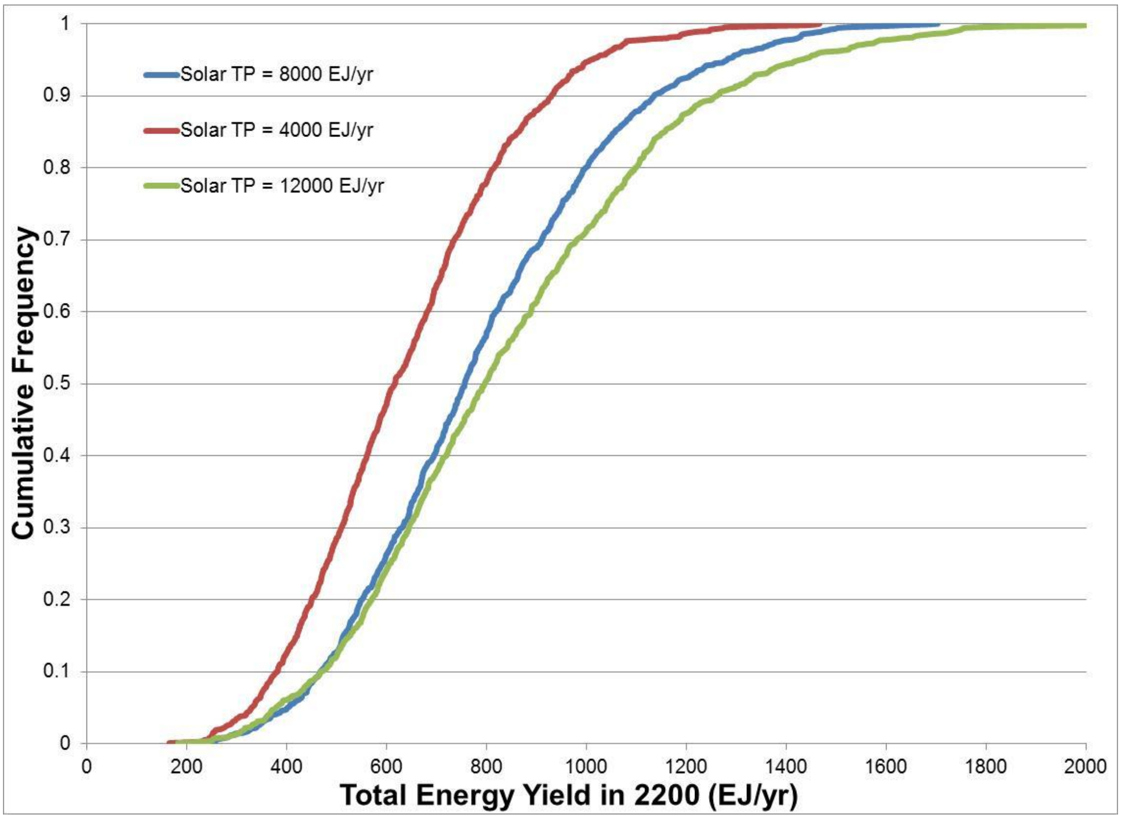


Figure 8-5. Comparison of cumulative frequency of values from Monte Carlo simulation for GEMBA output TOTAL ENERGY YIELD in 2200 using different values for . TP_{SOLAR}.

CHAPTER 9. DISCUSSION

The main purpose of this chapter is to summarise the results from the previous two chapters. A comparison is made between output from the GEMBA model, the IEA WEO (2008c) Reference Scenario (created using the WEM model) and three scenarios for total energy demand from the WEA (2000). A different, exogenous, function for energy demand is tested using the WEA scenarios. The dynamics of the GEMBA model are also explored in greater detail.

9.1. Summary of results

Throughout all of the scenarios explored in CHAPTER 7, the GEMBA model displayed stability to changes in the resource parameters. For instance, despite a doubling in the availability of energy resources over the baseline case, the TOTAL ENERGY YIELD and NET ENERGY YIELD still declined to around the level of the baseline case by the year 2200. The same pattern was repeated for changes in the EROI, and for changes in the CAPITAL FACTOR and the INCEPT DATE of renewable sources. In systems language the behaviour displayed by the energy-economy system is said to be self-regulating.

In CHAPTER 8, a greater area of the possibility space was explored. These results suggested that improvements in the EROI of solar and access to a larger technical potential over those used in the baseline case could certainly allow the energy-economy system to achieve TPES greater than currently consumed. The Monte Carlo simulation suggested that the current level of energy consumption lies beneath the 25 percentile of what might be achieveable by an energy system running solely on renewable energy.

The issue of energy quality was discussed in Box 5-1. Many renewable energy sources are used to generate electricity directly. Within the GEMBA methodology these include all forms other than BIOMASS. In the baseline run, 147 EJ of the 207 EJ produced in 2200, over 70%, is produced directly as electricity. This compares with present-day electricity consumption of 56 EJ/yr (IEA, 2008c)

9.2. Long-term energy future: economic vs. biophysical

Comparing the projections for the period to 2030 from the IEA WEO 2008 Reference Scenario (see Figure 9-1) with the baseline of the GEMBA model (see Figure 9-2), some marked differences are apparent. The most obvious is that the IEA predicts that conventional oil production will increase over the period, whereas the GEMBA model projects a peak and decline in production by 2030. This may be due to differences in how oil resources are classified within the WEM and GEMBA models. A similar observation can be made for conventional gas production, which the IEA predict to continue increasing, whereas the GEMBA model projects a plateau over the period to 2030.

The trend in coal production is similar within the projections from the two models; however the IEA projects a much greater increase over the period to 2030. Trends in biomass production are similar, again with the IEA predicting a greater increase than the GEMBA model. Other renewable sources show similar trends, increasing over the period 2005 to 2030. The increases projected by the IEA tend to be less dramatic than the GEMBA model.

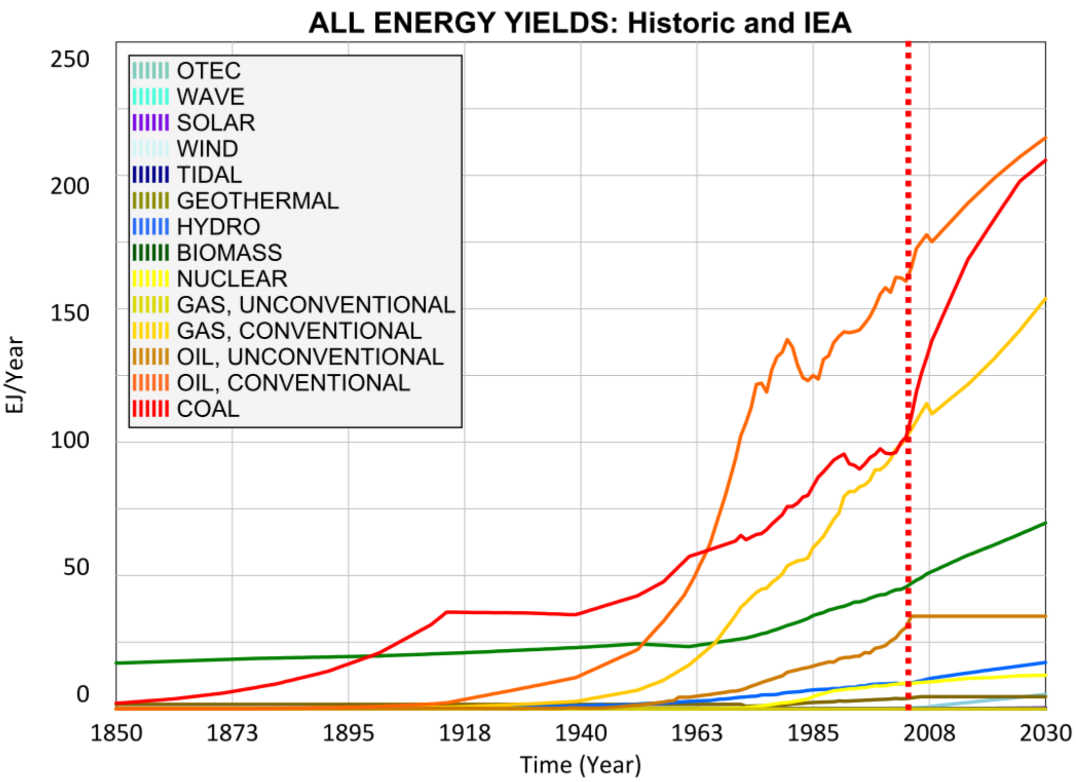


Figure 9-1 Historical production data (dots) plus linear interpolation of projections from IEA WEO (2008c) Reference Scenario (solid lines) using WEM model
The horizontal line for unconventional oil production in the period 2006-2030 reflects an absence of data from the IEA WEO.

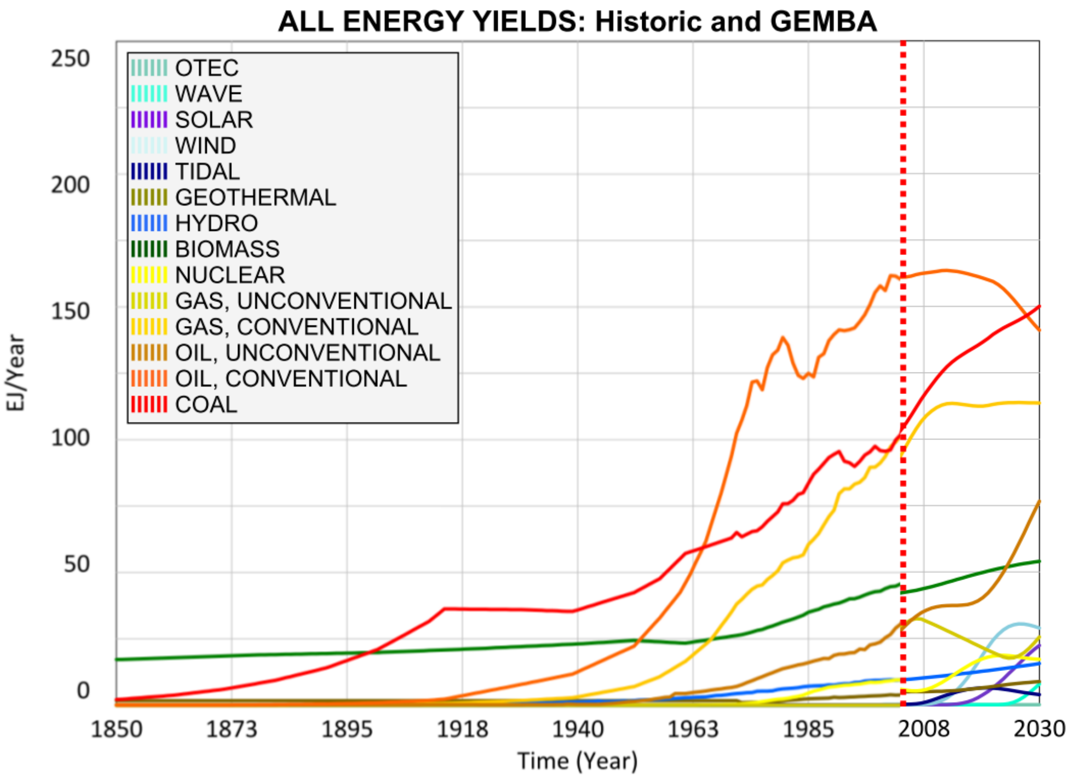


Figure 9-2 Production of energy from all sources of the baseline run, using the same colour coding as the IEA WEO 2008 Reference Scenario.
The projection to 2030 differs markedly from the IEA Reference Scenario, especially concerning conventional oil and gas production.

Within the *World Energy Assessment: Energy and the Challenge of Sustainability* (WEA, 2000), a collaboration between the United Nations Development Programme (UNDP), United Nations Department of Economics and Social Affairs (UNDESA) and the World Energy Council (WEC), a range of global primary energy requirements are predicted for the year 2100. These values are 1859 EJ/yr, 1464 EJ/yr and 880 EJ/yr reflecting high, middle and low growth scenarios respectively. The low growth scenario has a variant (C1) whereby 80-85% of this demand is supplied by renewable sources.

Figure 9-3 shows total energy demand from the WEA (2000) high (A), middle (B) and low (C) economic growth scenarios. Comparison of the WEA projections with the Monte Carlo scenarios produced with GEMBA in the last chapter is shown in Table 9-1. The output from the GEMBA model suggests that, from a biophysical perspective, both the middle and high economic growth scenarios from the WEA are unsustainable in the long term.

Table 9-1. WEA low, middle and high energy demand scenarios expressed as percentiles from the low, medium and high GEMBA scenarios from the Monte Carlo analysis.

		WEA Scenarios (EJ/yr)		
		Low 880	**Middle 1464**	**High 1859**
GEMBA Scenarios	**Low**	87	100	100
	Medium	68	97	100
	High	60	96	99

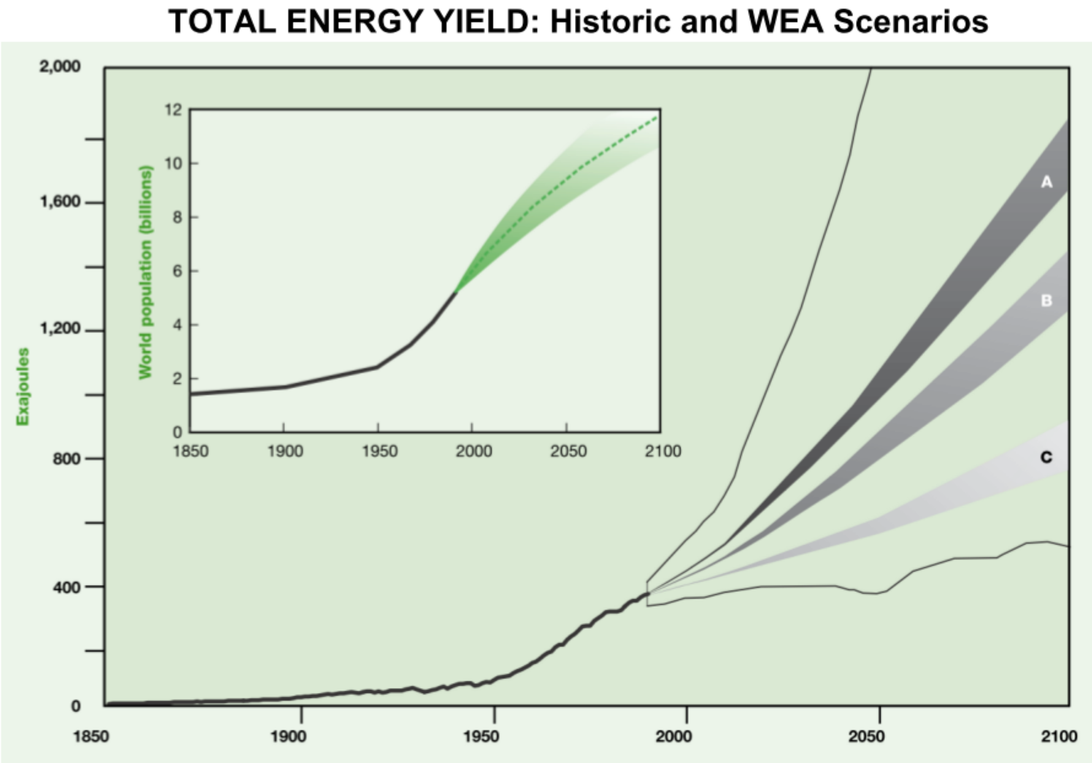


Figure 9-3. Three scenarios for total energy demand to 2100 from the WEA (2000, p. 345), including high (A), middle (B) and low (C) economic growth assumptions.
Insert shows global population from 1850-1990 and range of projections to 2100.

9.3. A different function for EROI

The analysis in the proceeding chapters uses the EROI function presented in CHAPTER 4, where total EROI is a function of two exponential components, an increasing technological component and a decreasing physical component. This section explores the effects of using a linearly decreasing function for the physical component of the EROI function. This linear function is defined by the equation:

$$H(\rho_k) = \varphi_k(1 - \rho_k) \qquad [9\text{-}1]$$

The Monte Carlo analysis method from Section 8.3 has been used with this new EROI function to generate a new set of results for the TOTAL ENERGY YIELD in 2200. The percentiles of the two EROI functions are compared in Table 9-2. Looking at the cumulative frequency plot of the GEMBA model output TOTAL ENERGY YIELD in 2200 for the two EROI functions, shown in Figure 9-4, the use of a linear EROI function delivers a lower TOTAL ENERGY YIELD in 2200 than the exponential EROI function for all but the top 10 percentiles. The current TPES, of around 500 EJ/yr, lies at the 40 percentile.

Table 9-2 Percentiles of total energy yield from Monte Carlo simulations for two EROI functions

Percentile	Exponential EROI Function (EJ/yr)	Linear EROI Function (EJ/yr)
25	591	375
50	756	611
75	951	888
95	1281	1333

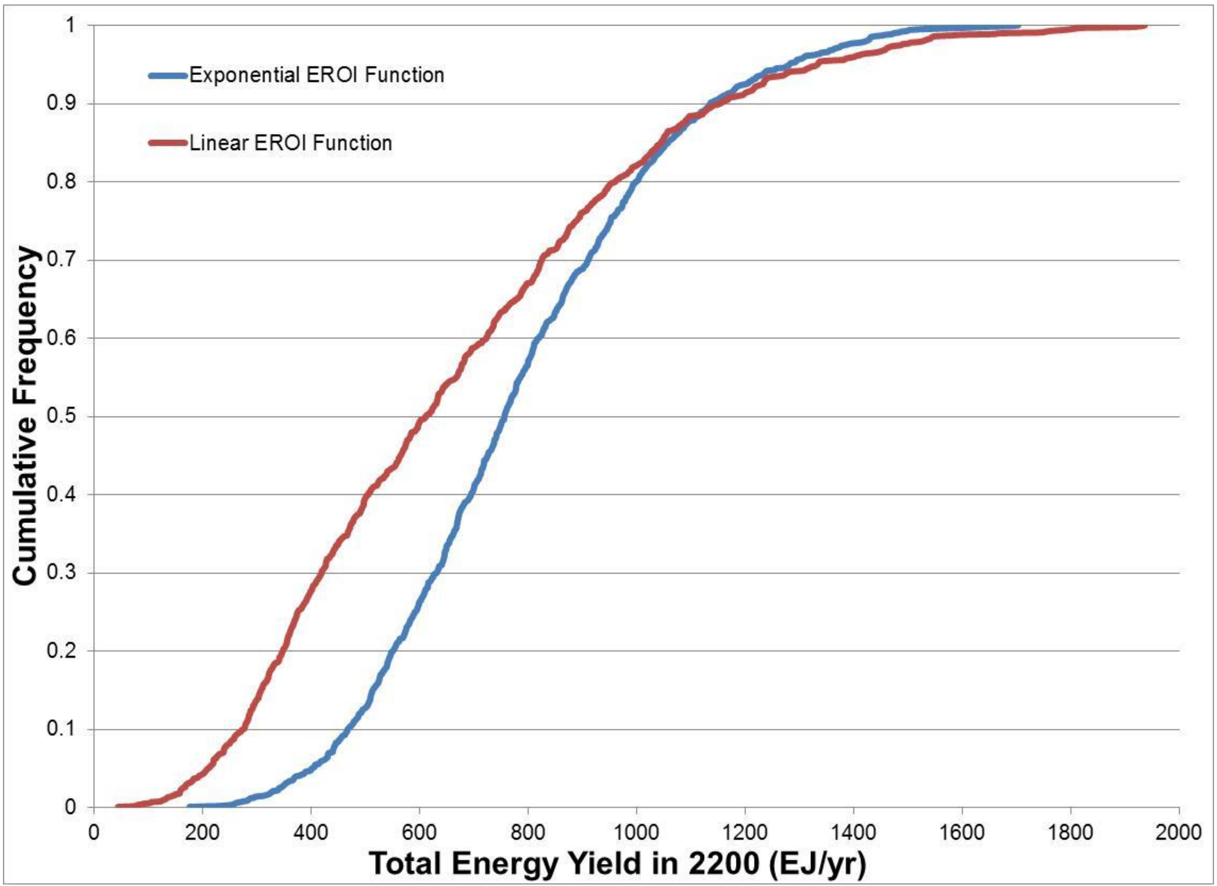


Figure 9-4 Cumulative frequency of values from Monte Carlo simulation for GEMBA output TOTAL ENERGY YIELD in 2200 using the exponential EROI function (blue line) or a linear EROI function (red line).

9.4. What if energy demand is not a function of capital stock?

Within the GEMBA model it is assumed that demand for energy is a function of industrial capital stock. This assumption is at odds with the conventional economic approach which assumes demand is a function of (normally) population, *per capita* desire for energy services and the efficiency of the energy system to deliver those services. Since these factors are outside the boundary of the GEMBA model an attempt to simulate this type of energy demand is made by substituting the demand curves from the WEA Scenarios into the GEMBA model using the baseline parameter values.

The results of using WEA Scenarios within the GEMBA model are displayed in Figure 9-5 and Figure 9-6 with the baseline run as comparison. Using these demand projection the TOTAL ENERGY YIELD does indeed increase approximately exponentially until 2100. However, in all three cases, the NET ENERGY YIELD declines to a level of around 400 EJ/yr in 2100, despite the high TOTAL ENERGY YIELD, meaning that in Scenario A, around 70% of the energy produced is used simply in subsidising the energy sector.

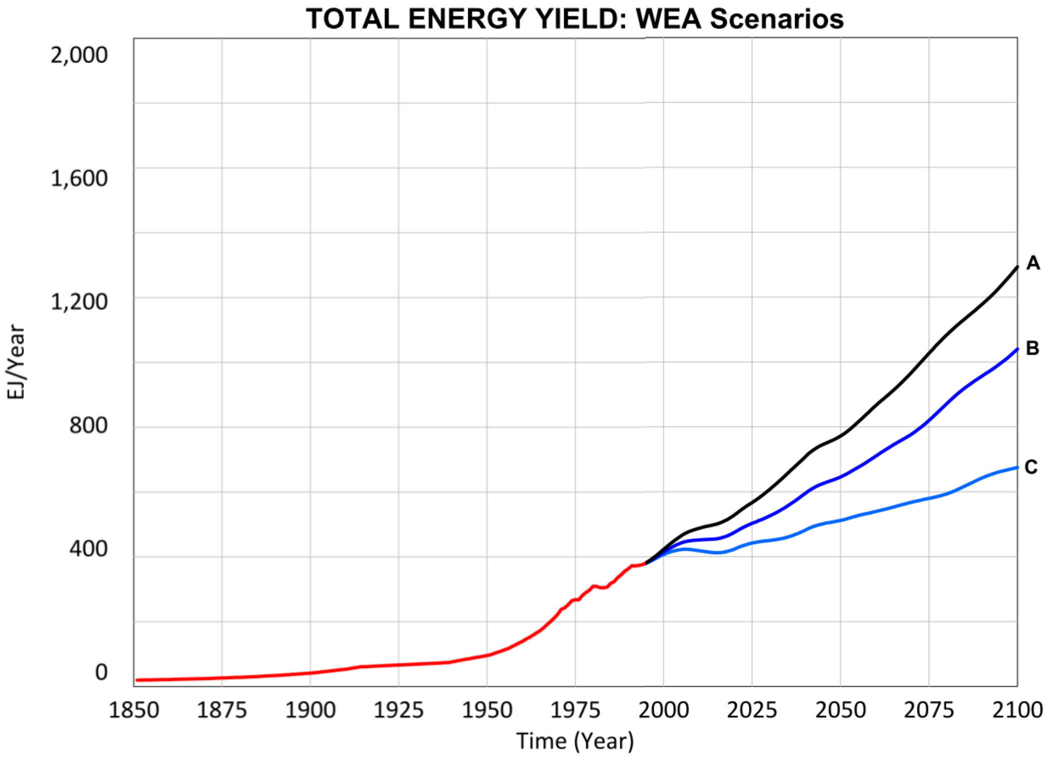


Figure 9-5. Sensitivity analysis of TOTAL ENERGY YIELD to the demand projections from the WEA A – high growth (black line), B – middle growth (dark blue line) and C – low growth (light blue line) scenarios within the GEMBA model.
The red line shows historic production data.

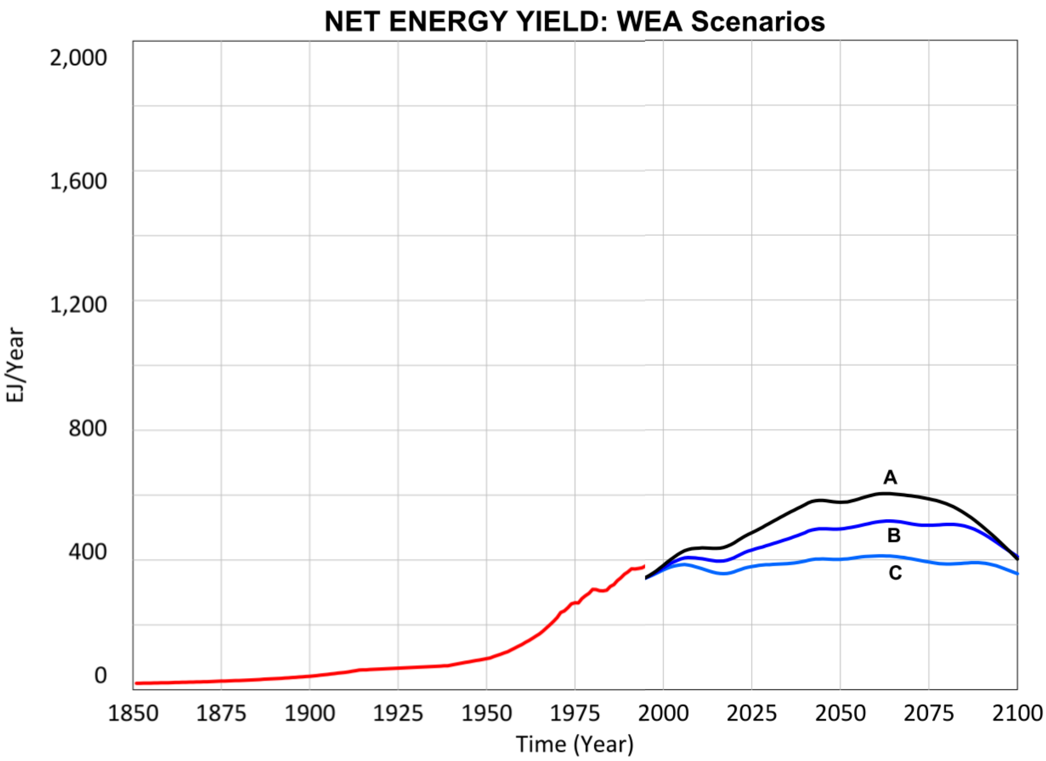


Figure 9-6. Sensitivity analysis of NET ENERGY YIELD to the demand projections from the WEA A – high growth (black line), B – middle growth (dark blue line) and C – low growth (light blue line) scenarios within the GEMBA model.
The red line shows historic production data.

9.5. Further understanding the energy-economy system

> "as the magnitude of the renewable energy system rises, the HMC (human made capital) that must be diverted to their maintenance slowly becomes an increasing burden, and cannot be maintained as well as other demands" (Malcolm Slesser, et al., 1997, p. 238)

What is the reason for the self-regulating behaviour of the energy-economy system? There exists a dynamic balance between the energy sector and the rest of the economy characterised by the attributes of the various energy sources that make up the energy sector. Within the GEMBA model, those attributes are defined by the model parameters: INCEPT DATE_k, $\text{URR}_{\text{NON-RENEWABLE}}$ or $\text{TP}_{\text{RENEWABLE}}$, EROI_k and CAPITAL FACTOR_k of the energy sources which determine the flows of energy and physical capital passed between the energy sector and the rest of the economy.

The annual flow of non-renewable energy sources is limited only by the capital stock directed towards their extraction. This is not so in the case of renewable energy sources, whose flow is limited. These energy sources are also characterised by a larger capital requirement, meaning that when the energy-economy system transitions to the use of mainly renewable energy sources, a greater flow of physical capital per unit of delivered energy must be directed away from the industrial sector to the energy sector. This is illustrated by plotting INDUSTRIAL CAPITAL STOCK as a function of the sum of all RENEWABLE ENERGY CAPITAL STOCK, i.e. $\sum Cap_{RENEWABLE}$ as in Figure 9-7. In this case, the baseline values are used but the time horizon has been expanded to the year 10,000. The balance between the energy sector and the rest of the economy tends towards a particular point.

The value of the CAPITAL STOCK attractor is determined by the energy sources, each of which tends toward that level of PRODUCTION at which it achieves the maximum ENERGY ACCESSIBILITY. This is illustrated by plotting ENERGY $\text{ACCESSIBILITY}_{\text{BIOMASS}}$ as a function of ANNUAL $\text{PRODUCTION}_{\text{BIOMASS}}$ as in Figure 9-8. The value of the attractor in the ENERGY ACCESSIBILITY-ANNUAL PRODUCTION plot determines the level of CAPITAL STOCK that each of the renewable energy sources will tend towards, the sum of which then affects the level of the INDUSTRIAL CAPITAL STOCK.

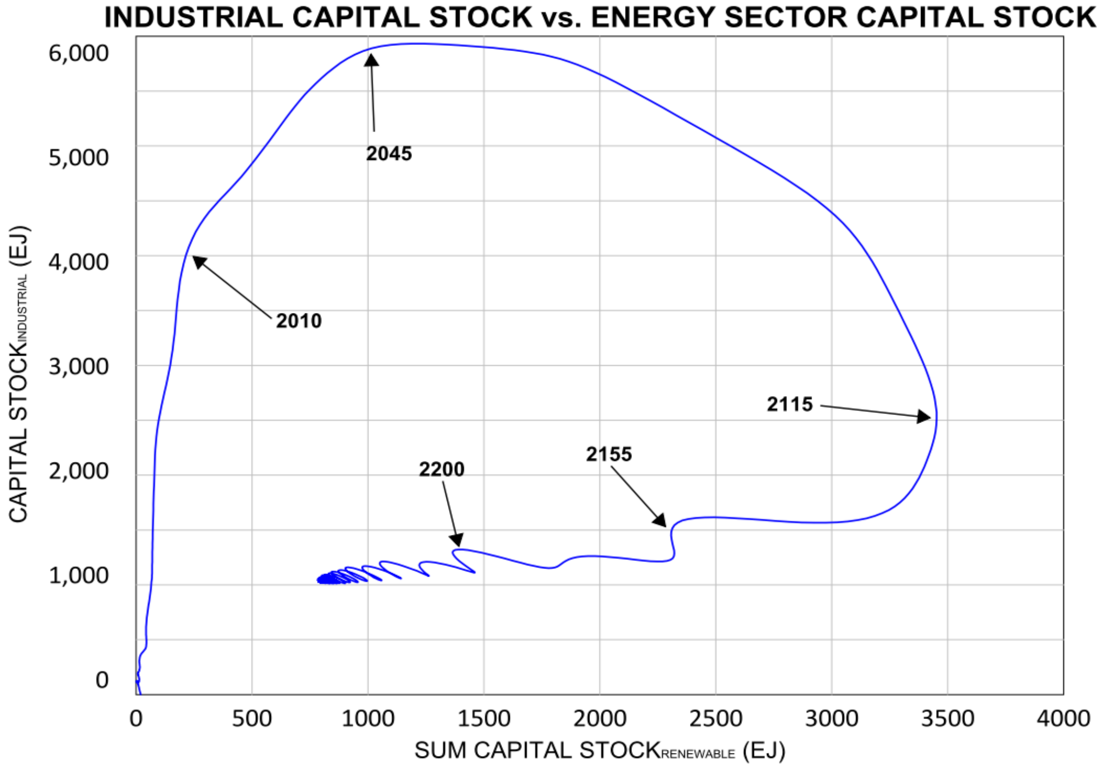


Figure 9-7. **INDUSTRIAL CAPITAL STOCK vs. TOTAL RENEWABLE CAPITAL STOCK**
INDUSTRIAL CAPITAL STOCK (vertical axis) plotted as a function of TOTAL RENEWABLE CAPITAL STOCK (horizontal axis, both in units of EJ) from the baseline run with the time horizon expanded to the year 10,000. The balance between the energy sector and the rest of the economy tends towards a particular point.

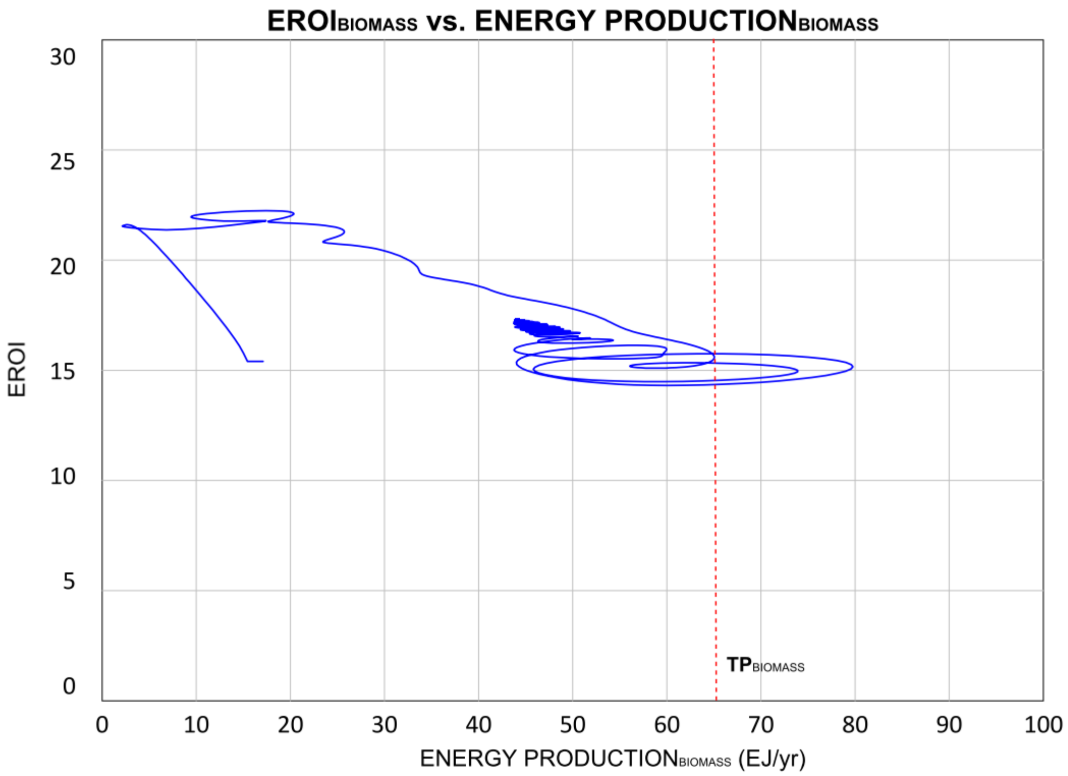


Figure 9-8 **$EROI_{BIOMASS}$ vs. ENERGY $PRODUCTION_{BIOMASS}$**
$EROI_{BIOMASS}$ as a function of the ENERGY $PRODUCTION_{BIOMASS}$ using baseline values with the time horizon expanded to the year 10,000. The annual production tends toward a particular point.

Figure 9-9 shows the TOTAL ENERGY YIELD plotted as a function of AGGREGATE CAPITAL INTENSITY for the baseline run. In this plot there is an attractor constraining high CAPITAL INTENSITY to values of TOTAL ENERGY YIELD below a level 250 EJ/yr, around half our current energy consumption, when using the baseline values for the resource parameters.

The reason for this behaviour is explained by Figure 9-10. The global energy system has evolved such that over 80% market-share of TPES currently comes from fossil fuels, which have very low capital requirements. The present state of the system represents a valley. A transition away from fossil fuels represents ‘climbing the valley walls’ which will necessarily require greater amounts of capital from the main economy, which may stymie re-investment of capital into the economy and cause a slow in the growth of its capital stock. Energy demand also slows, since energy demand is a function of economic capital stock.

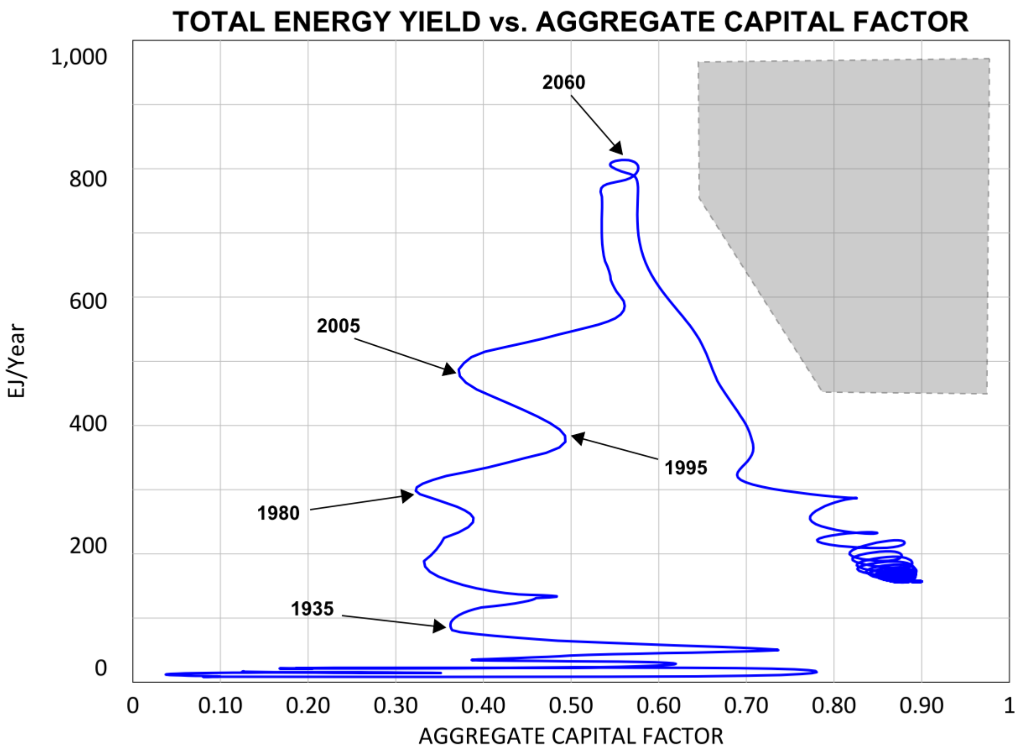


Figure 9-9. TOTAL ENERGY YIELD vs. AGGREGATE CAPITAL FACTOR
TOTAL ENERGY YIELD plotted as a function of AGGREGATE CAPITAL FACTOR. The model was run until the year 10,000 to allow the system to reach a level of dynamic balance. After the model has undergone a transition to renewable energy sources, the TOTAL ENERGY YIELD of the baseline run decreases.

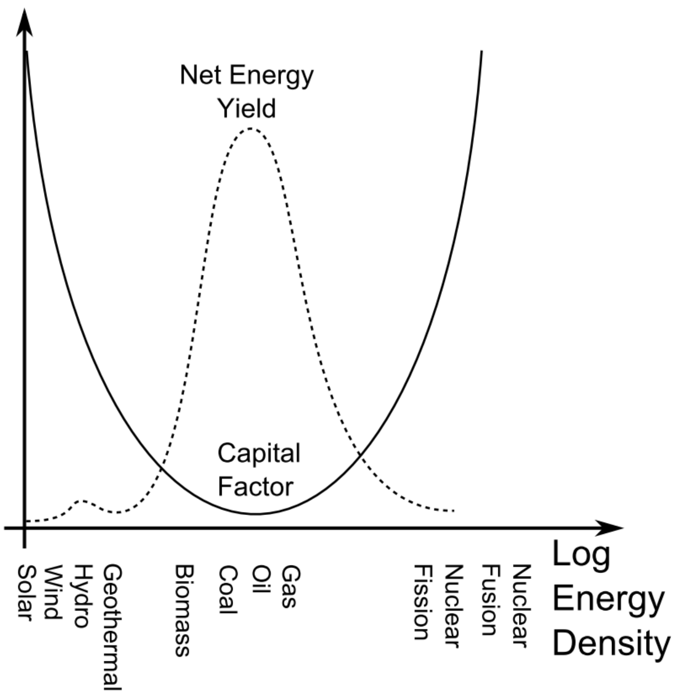


Figure 9-10. The 'valley of stability'.
Graph showing capital factor and current market share of global energy system as a function of energy density in J/kg. 80% of TPES is currently supplied by fossil fuels with low capital factor. Any move away from these sources represents an increase in capital that must be supplied by the main economy.

CHAPTER 10. REFLECTIONS

In this chapter, a critical look at the systems modelling approach used in constructing the GEMBA model is made by exploring the effects of some of the assumptions made within the methodology. The implications of the results from the GEMBA model are then discussed for both engineering and technology research and for energy policy. This critique enables the identification of some potentially fruitful directions for further development of the model. This is followed by some final conclusions for the project overall.

10.1. Assumptions of the GEMBA methodology

The GEMBA model makes a number of explicit assumptions about the nature of the global energy-economy system. These are summarised as:

1. that the energy-economy system is thermodynamically open, exchanging both energy and materials with its environment and that those exchanges are subject to the laws of thermodynamics;
2. that the behaviour of the global social-economic system is defined primarily in terms of physical activities (the *biophysical* systems assumption);
3. that growth of the system is a result of the creation of human-made capital thereby increasing the capacity of the system to exploit energy resources;
4. all physical and economic activity is ultimately constrained by the availability of energy supply;
5. that energy demand and supply are interdependent;
6. that the human-made capital (economic infrastructure) generates both demand for consumption as well as providing the factors of production;

7. that demand for energy is *aggregated* and dependent only on the size of the industrial capital stock;
8. that energy sources are totally *substitutable*;
9. that the global social-economic system is simplified to the interactions of just two interdependent, but separable components (or sectors): the industrial and the energy sectors;
10. that the behaviour of each of the energy sources that make up the energy sector are characterised by four variables: *incept date*, *availability*, *EROI* and *capital factor*;
11. that accessibility of an energy source is characterised as a *continuous, peaking function* of the production of that energy source;
12. that allocation between energy sources is fundamentally dependent only on physical factors;
13. that the capital needs of the energy sector take *priority* over the needs of the rest of the economy;

The influence of each of these assumptions on the model results is now discussed.

The assumption that the energy-economy system is subject to the laws of thermodynamics needs no discussion, since to assume the converse is to negate the possibility of any physical analysis. This assumption underpins the second, biophysical assumption. It allows examination of the system in terms of fundamental, irrefutable physical laws. The biophysical assumption also entails that any consideration of price is unnecessary. This is a major departure from economic analysis.

From this assumption flow the next two assumptions, that the growth of the system, i.e. increasing the stock of human-made-capital is dependent on securing appropriate supplies of energy from the environment and that all physical and hence economic, activity is dependent on these supplies.

A major assumption of the GEMBA methodology is that energy supply and energy demand are inter-related. This is achieved by assuming that energy demand is a function of the amount of human-made-capital and hence defined endogenously within the model. This is different to economic models, which usually define energy demand exogenously as a function of population and income, or as a function of GDP. The effects of changing to an exogenously defined energy demand function were explored within Section 9.3.

Within the GEMBA model it is assumed that there is demand only for an aggregated *energy*, as opposed to demand for a specific *energy form*, such as petrol or electricity or even for an *energy service*, such as space heating or lighting. This is a simplification. The supposition is underpinned by the assumption that energy sources are substitutable in meeting energy demand. Justification for this assumption was based on two factors. Firstly, that demand for certain energy services, such as transport, whilst non-substitutable in the short-term, changes between different energy sources in the long-term and that the horizon of the GEMBA model was such that this effect would be significant. The second factor was one of pragmatism: that historical data does not record how energy was used in the past; only that it was used. There is no information to determine what proportion of the coal produced in 1850 was used for transport, what proportion for industry, what proportion for heating, etc. Since the GEMBA model uses historical data for calibration, demand disaggregated by end-use could not be calibrated – the allocation of demand would be pure assumption.

Changes in demand between energy sources require infrastructural changes on the scale of decades, since a piece of technology is normally constructed to utilise only one energy source. In the case of electricity generation, the lifetime of power stations (often on the scale of 30-40 years) may be a significant factor in the substitution between sources. Data on energy end-use is available for the recent past, at least as far back as 1990 (Taylor, d'Ortigue, Francoeur, & Trudeau). Such data may begin to hint at the dynamics of such changes, but more long-term data is required.

The use of an aggregated energy demand function does not affect the main conclusion that "renewable energy sources cannot support current energy consumption levels" since any inflexibility in substitution between energy sources would serve to make the system less flexible overall, hence even less likely to be able to meet continued high energy demands.

Within the GEMBA model, the economy is represented by just two sectors: the energy sector and the industrial sector. Obviously the real economy has many more interacting sectors. The possibility of disaggregating the model into more sectors is explored in Section 10.3.3. What affect does this assumption have on the results from the model? Disaggregation of the economy would give a more detailed picture of the flows of energy and materials within the economy, but would not change the total amount of energy flowing, nor change the amount of capital required by the energy sector, so should not fundamentally change the results from the model.

Within the GEMBA methodology, energy resources are assumed to be exhaustively defined by the four factors: incept date, availability (URR or TP), EROI and capital factor. This is a simplification. Using only the four factors of the GEMBA model limits the dynamics that may be analysed. Within the real world system, energy resources may be characterised using other properties, most notably by cost in economic analyses. However, the inclusion of cost into the GEMBA methodology would have the effect of either making some processes financially economic (such as when certain processes are subsidised), when they are not energetically economic (i.e. do not provide positive net energy yield) or, *visa versa*, to make them financially inviable when they are still energetically viable. Either situation would limit the net energy yield of the whole system; hence inclusion of price dynamics would have little effect on the main conclusion that a reduction in energy supply is inevitable.

The dynamic function for EROI is the main component of the GEMBA methodology and is described fully in CHAPTER 4. This peaking function entails that energy returns cannot increase monotonically through the production cycle. The shape of the curve is based on fundamental physical principles: that energy returns are subject to strict physical limits and that sites offering the best energy returns are likely to be exploited first.

In CHAPTER 8, the self-regulatory behaviour of the GEMBA model was seen to be due mainly to the high capital factor of renewable energy sources. Changing the EROI function such that it was constant or increased as a function of production would alter the results by increasing the level of energy supply at which the system was in dynamic balance. However, there is no good physical reason why the EROI of an energy source should remain constant or increase through the production cycle.

In economic analyses allocation of resources is based on price and substitutability between resources. Allocation between energy sources within the GEMBA model is based purely on two physical factors: the EROI and the proportion of unexploited resource. In CHAPTER 7, the sensitivity of model outputs TOTAL ENERGY YIELD and NET ENERGY YIELD was tested to changes in both EROI and total resources. These analyses did not change the main conclusion that renewable energy sources cannot support current TPES. Using a different allocation function would have little effect on this conclusion, since the self-regulatory behaviour of the GEMBA model was seen to be due mainly to the high capital factor of renewable energy sources.

Within the GEMBA model, the capital needs of the energy sector and any remaining capital is re-invested into the main economy. Changing this situation such that the capital needs of the main economy took priority over the energy sector would have little effect on the results since any under-investment in the energy sector would lead to a lack of NET ENERGY YIELD to be embodied as INDUSTRIAL OUTPUT and hence decrease re-investment into the main economy.

10.1.1. Energy as the only metric

Some of the issues of using only one metric within the model have been discussed previously (see Section 5.2.3). The main problem is that, whilst the availability of energy may represent an absolute fundamental constraint on physical activity, other constraints, such as non-availability of mineral resources, human labour or financial investment, may curtail economic activity before energy constraints come into force.

A further problem results from the use of only one metric within the GEMBA model; an inability to model improvements in the efficiency of energy use. Since there is no measure of the amount of industrial output, other than in terms of energy, when faced with a reduction in the energy embodied in that output it must be assumed that less production occurred. The decrease in energy cannot be attributed to efficiency gains since there is no independent measure of production. A simple solution would be to utilise a double set of accounts by introducing another metric. However, while standard econometric models may be thought to obviate this problem by using both energy and price as metrics, this is not the case since price is simply a relative measurement. A reduction in, say, industrial output in terms of energy at a stable monetary value, say 15 MJ/$ to 10 MJ/$, may not necessarily signal an increase in efficiency. If, however, another physical metric, such as mass, is introduced, then it may be guaranteed that a production process changing from 15 MJ/kg to 10 MJ/kg truly represents a gain in efficiency.

How do these assumptions compare with those underpinning econometric energy models? Below is a list of assumptions identified during analysis of the economic energy models WEM, MESSAGE and MARKAL:

1. that financial costs of energy technologies may be forecast over a time period of decades;
2. that costs of so-called ‘backstop’ technologies (W. D. Nordhaus, 1973) are independent of market price;
3. that increases in the market price of energy increase the economically available resources, such that “market forces will always (and promptly!) generate enough supply to meet demand” (Abt, 2002);
4. that energy demand is independent of energy supply;
5. that energy demand is a function of population and *per capita* demand for energy services or a function of GDP;

6. that economic growth will continue (this is assumed either explicitly or implicitly through the use of a discounted value on future investments)
7. that all available resources may potentially become economically accessible;
8. that GDP (i.e. economic performance) is independent of energy supply;
9. that economic data represent an “optimal response to the current price vector” (IEA, 2007a, p. 9)

It is clear that there are many differences between the two sets of assumptions. The two most fundamental differences are that the GEMBA methodology is founded on physical laws and that it recognises the fundamental intractability of constraints.

10.2. Implications of the GEMBA model results

The results of the GEMBA model suggest that the behaviour of the energy-economy system is self-regulating. Not all levels of energy demand can be delivered by an energy system running solely on renewable energy. The high and middle growth scenarios from the WEA lie above the 95 percentile of what may be sustainable using solely renewable energy. This suggests that such development pathways are not sustainable in the long term.

If it is accepted that the GEMBA model adequately represents the global energy-economy system, then these results have definite implications for both engineering and technology research and for energy policy.

10.2.1. Implications for engineering and technology research

The GEMBA model results show that use of finite, non-renewable resources now means that these resources are not available for future generations. Furthermore, renewable energy supplies might not be able to meet present levels of TPES after non-renewable resources have been used, therefore future generations might have less energy supply available than at present. This means that reducing energy demand might be necessary, perhaps not today, but at some point in the not-too-distant future.

The implication for engineering and technology research is that a major focus of energy research should be in the field of *demand reduction to fit within existing energy constraints*. This may be achieved at many levels from improving the efficiency of single systems right up to technologies which enable re-organisation of social structures to lower energy intensive patterns.

Research also needs focus, not just on reducing the monetary cost of energy technologies, but also on increasing the EROI, i.e. on reducing the energetic costs of production. As discussed in CHAPTER 2, economic and energetic analyses may offer divergent (E)ROI metrics, especially where labour-intensive processes are concerned. Research also needs to focus on reducing use of material inputs to production processes, especially those using constrained resources

Another important area for research is explicitly determining energy resources in terms of their net energy yield, rather than in terms of monetary costs, as is done presently. To better plan for the future, we must gain better understanding of how the EROI of an energy source changes over the entire production cycle of that resource. Within this work, it was postulated that the same function might serve for all resources; however, this may not necessarily be the case. More work needs to be done in this field. One possibility is the addition of a third dimension of 'net energy yield' to the McKelvey diagram of resource classification.

10.2.2. Implications for energy policy

The results of the GEMBA model suggest that the energy-economy system is self-regulating in its behaviour. Sustainable energy policy depends on aligning decision making with the natural tendency of the system and determining the optimal path between the position in which we are now and that of long-term stability of the system.

Recognition that current energy levels might not be sustained using renewable energy sources could (and perhaps should) result in energy policies that would attempt to curb or even reverse the current trend of increasing energy demand. How this might be achieved is a matter of some considerable debate, given an increasing global population and an assumed increase in material living standards for all.

Since decline in energy supply is a possibility, policy must plan either for how society can achieve the same service using less energy, or on how we might 'make do with less'. This is a huge paradigm shift from our current societal value system, which touts economic growth, euphemistically referred to as 'development', as the solution to most social problems. Slesser et al.(1997) suggest this may require changing current notions of 'development', saying,

> "countries currently in the transition from under-developed (in the current sense) to developed would do well not to imitate the pattern of the presently developed countries. They should seek to

create a simple, durable infrastructure that can operate on a low input of energy" (Malcolm Slesser, et al., 1997, p. 240)

10.3. Future development of the GEMBA methodology

What are the future directions for research open to the GEMBA methodology? There seem to be two avenues for fruitful investigation: the development of distinct modules, such as population or natural resources, to enable the development of broader scenarios, and the integration of the GEMBA model with existing econometric models, such as MESSAGE or MARKAL.

10.3.1. Separate modules

The development of distinct modules dealing with a variety of important interdependent factors would increase the ‘lens’ through which the GEMBA model views the world, allowing for distinct multi-perspective scenarios. Two obvious candidates would be the development of a population module to project various population growth scenarios and the development of a natural (non-energy) resources module.

The inclusion of a population module would most likely necessitate the disaggregation of the global production and consumption of energy into distinct regions (or socio-economic brackets) since the use of average per capita data gives a distorted picture of reality.

The advantage of including natural resources would be to include another set of physical accounts, most probably in the form of mass. This would obviate problems discussed earlier of having only one metric within the GEMBA model. Such a module could in form be very similar to the energy sector module with similar parameter for resources such as availability, accessibility and capital factor but with EROI values of less than one, to reflect that the extraction of non-energy resources, by nature, down-grades energy resources into less useful forms.

10.3.2. Disaggregation of energy demand

Disaggregation of energy demand into various secondary energy carriers such as oil and coal products (petroleum, coke, etc.) and electricity, as well as distinguishing various end-use energy services, such as heating, agriculture, transport, process and lighting. The issue of how demand varies between these end-uses over long periods of time (discussed in Section 10.1), must be borne in mind.

10.3.3. Disaggregation of the economy

Disaggregation of the economy into different sectors would give a greater understanding of the energy and material flows through the whole system and give a more realistic representation of the economy. One possibility would be to distinguish the industrial, transport, commercial and residential sectors. This approach would best be carried out simultaneously with disaggregation of energy flows through the economy into energy carriers and end-use services.

10.3.4. Integration with econometric models

Another direction for future research might be to investigate the possibility of integrating the GEMBA model into current econometric energy models. GEMBA could sit within existing energy modelling suites, to serve as a biophysical ‘reality check’ to the output of such economic modelling packages as MESSAGE, MARKAL or WEM (Messner & Strubegger, 1995; OECD/IEA, 2009; Regemorter & Goldstein, 1998).

Integration of GEMBA with other energy modelling suites could be explored by determining the compatibility between various model components. This may necessitate additional ‘translation’ software or re-development of the GEMBA model in a different language.

CHAPTER 11. CONCLUSIONS

The GEMBA methodology was developed as a means to explore the long-term potential of substituting renewable energy sources for present non-renewable consumption. The methodology was compared and contrasted with other approaches that are used to study the global energy-economy system, including the standard neoclassical economic approach used in such models as MESSAGE and MARKAL.

A number of meta-analyses were conducted in support of the GEMBA model. These include:

- meta-analysis of estimates of historic energy production from all energy sources;
- meta-analysis of estimates of the magnitude of global energy resources for all energy sources;
- meta-analysis of estimates of energy-return-on-investment (EROI) for all energy sources.

The GEMBA methodology developed uses a systems dynamic modelling approach utilising stocks and flows, feedback loops and time delays to capture the behaviour of the global energy-economy system. The system is decomposed into elements with simple behaviour that is known through energy analysis. The interaction of these elements was captured mathematically and run numerically via the systems dynamics software package, VenSim. Calibration of the model was achieved using historic energy production data from 1800 to 2005.

The GEMBA methodology uses fundamental physical principles from net energy analysis, together with a systems dynamic modelling approach to assess the possible availability of energy to the energy-economy system in the future. The core of the GEMBA methodology constituted the description of a dynamic EROI function over the whole production cycle of an energy resource from initial development, through maturation to decline in production, in the case of non-renewable resources, or to the technical potential in the case of renewable resources.

Using the GEMBA methodology, the global energy-economy system was identified as a self-regulating system. The self-regulating behaviour acts to constrain the amount of total primary energy supply that the system can produce under a renewable-only regime. A number of analyses were conducted to test the sensitivity of the system to changes in:

- the technical potential of renewable resources;
- the EROI of renewable resources;
- the capital intensity of renewable resources and;
- the energy intensity of the economy,

A Monte Carlo analysis over the full range of estimates for EROI and technical potentials of renewable resources, found in the meta-analysis of CHAPTER 6, was also conducted.

The results from the modelling suggest the high and middle growth energy demand scenarios are unsustainable in the long term and that even current energy consumption levels might not be possible indefinitely. This finding has stark implications for the future direction of both engineering and technology research as well as for energy policy. These implications were discussed.

Standard econometric energy models use price dynamics to model the energy-economy system. Those used to dealing with standard econometric models may not like the conclusion presented here. In which case, who might benefit from this analysis? Many people within the engineering and physical sciences community should appreciate and have an affinity with the methods used in this study. In light of the main conclusion, it seems wise that a strong focus for future research within this community should be on the technology of ‘doing more with less’ — on producing equipment that increases productivity but uses less energy; on finding ways to reduce energy demand whilst not sacrificing quality of life.

REFERENCES

Abt, C. C. (2002). The Future of Energy. In R. N. Cooper & P. R. G. Layard (Eds.), *What the future holds : insights from social science* (pp. 285 p.). Cambridge, Mass.: MIT Press.

Ackermann, T. (2005). *Wind power in power systems*. Chichester, West Sussex, England: John Wiley.

Adams, R. (1978). STRATEGIES OF MAXIMIZATION, STABILITY, AND RESILIENCE IN MESOPOTAMIAN SOCIETY, SETTLEMENT, AND AGRICULTURE. *Proceedings, American Philosophical Society (vol. 122, No. 5, 1978), 122*(5), 329.

Adams, R. M. (2001). Complexity in Archaic States. *Journal of Anthropological Archaeology, 20*(3), 345-360.

Akai, M., Nomura, N., Waku, H., & Inoue, M. (1997). Life-cycle analysis of a fossil-fuel power plant with CO2 recovery and a sequestering system. *Energy, 22*(2-3), 249-255.

Al-Husseini, M. (2006). The debate over Hubbert's Peak: a review. *GeoArabia, 11*(2).

Alberta Grain Commission (2000). *Ethanol Production in Alberta*: Interdepartmental Ethanol Committee, Government of Alberta.

Albin, S. (1997). *Building a System Dynamics Model Part 1: Conceptualization*: Massachusetts Institute of Technology.

Aleklett, K., & Campbell, C. J. (2002). *Proceedings of the First International Workshop on Oil Depletion,* Uppsala, Sweden.

Alessio, F. J. (1981). Energy Analysis and the Energy Theory of Value. *The Energy Journal, 2*(1), 61-75.

Allen, S. R., Hammond, G. P., & McManus, M. C. (2008). Energy analysis and environmental life cycle assessment of a micro-wind turbine. *Proceedings of the Institution of Mechanical Engineers Part a-Journal of Power and Energy, 222*(A7), 669-684.

Alsema, E. A.; de Wild-Scholten, M. J. & Fthenakis, V. M. (2006) Environmental impacts of PV electricity generation - a critical comparison of energy supply options. In: *Proceedings of the 21st European Photovoltaic Solar Energy Conference,* Dresden,Germany, 4-8 September 2006

Andersson, B. A., & Jacobsson, S. (2000). Monitoring and assessing technology choice: the case of solar cells. *Energy Policy, 28*(14), 1037-1049.

Andrews, S., & Udall, R. (2003). *Oil Prophets: Looking at World Oil Studies over Time*. Paper presented at the ASPO Conference.

Archer, C. L., & Jacobson, M. Z. (2005). Evaluation of global wind power. *Journal of Geophysical Research, 110*.

Armstrong, G. (1974). World coal resources and their future potential. *Phil. Trans. R. Soc. Lond. A., 276*, 439-452.

Arthur, S. (1982). *Oil Resource Estimates - How Much do we Know?* Laxenburg, Austria: Institute for Applied Systems Analysis.

Asif, M., & Muneer, T. (2007). Energy supply, its demand and security issues for developed and emerging economies. *Renewable and Sustainable Energy Reviews, 11*(7), 1388-1413.

ASPO (2001-2009). Newsletters: Association for the Study of Peak Oil.

Ayres, R. U. (1998). Rationale for a physical account of economic activities. In P. Vellinga, F. Berkhout & J. Gupta (Eds.), *Managing a material world : perspectives in industrial ecology : an edited collection of papers based upon the international conference on the occasion of the 25th anniversary of the Institute for Environmental Studies of the Free University Amsterdam, the Netherlands* (pp. 1-20). Boston ; London: Kluwer Academic.

Ayres, R. U., Ayres, L. W., et al. (2003) Exergy, power and work in the US economy, 1900-1998, *Energy, 28*(3), 219-273.

Ayres, R. U., Kneese, A. V., & D'Arge, R. C. (1970). *Economics and the environment : a materials balance approach*. Washington: Resources for the Future; distributed by the Johns Hopkins Press, Baltimore.

Ayres, R. U., & Nair, I. (1984). Thermodynamics and economics. *Physics Today, 37*(11), 62-71.

Ayres, R. U., Turton, H., & Casten, T. (2007) Energy efficiency, sustainability and economic growth, *Energy, 32*(5), 634-648

Baines, J. T., & Peet, J. (1983). *The dynamics of energy consumption : changing expectations for the supply of goods and services*. Christchurch, N.Z: Dept. of Chemical Engineering.

Bakis, R. (2007). The Current Status and Future Opportunities of Hydroelectricity. *Energy Sources, Part B: Economics, Planning, and Policy, 2*(3), 259 - 266.

Ballentine, T. (1973). *A net energy analysis of the use of Northern Great Plains surface mined coal in load center power plants*. Paper presented at the International Conference on Environmental Sensing and Assessment.

Banerjee, S., Duckers, L. J., Blanchard, R., & Choudhury, B. K. (2006). Life cycle analysis of selected solar and wave energy systems. *Advances in Energy Research 2006*.

Barnes, D. F., & Floor, W. M. (1996). RURAL ENERGY IN DEVELOPING COUNTRIES: A Challenge for Economic Development 1. *Annual Review of Energy and the Environment, 21*(1), 497-530.

Barnett, H. J., & Morse, C. (1963). *Scarcity and growth : the economics of natural resources availability*. [Washington]: Published for Resources for the Future by Johns Hopkins Press, Baltimore.

Barreto, L., & Kypreos, S. (1999). *Technological Learning in Energy Models: Experience and Scenario Analysis with MARKAL and the ERIS Model Prototype*.

Barstow, S., Mørk, G., Mollison, D., & Cruz, J. (2003). The Wave Energy Resource. In J. Cruz (Ed.), *Energy: Current Status and Future Prospects*: Springer.

Bateson, G. (1972). *Steps to an ecology of mind*. New York: Ballantine Books.

Battjes, J. J. (1999). *Dynamic Modelling of Energy Stocks and Flows in the Economy (An Energy Accounting Approach).* Unpublished Thesis (doctoral), The Author,

Rijksuniversiteit Groningen, 1999., [Groningen].

Bauman, H., & Tillman, A.-M. (2004). *The hitch hiker's guide to LCA : an orientation in life cycle assessment methodology and application*. Lund, Sweden: Studentlitteratur.

Bauquis, P. R. (2003). Reappraisal of energy supply-demand in 2050 shows big role for fossil fuels, nuclear, but not for nonnuclear renewables. *Oil & Gas Journal, 101*(7), 20-29.

Bennet, D. (2006). *Submission on Biofuels - Supplementary Document*: ASPO Australia - Biofuels Working Group.

Bentley, R. W. (2002a). Global oil & gas depletion: an overview. *Energy Policy, 30*(3), 189-205.

Bentley, R. W. (2002b). Oil Forecasts, Past and Present. *Energy Exploration & Exploitation, 20*, 481-491.

Bentley, R. W., Mannan, S. A., & Wheeler, S. J. (2007). Assessing the date of the global oil peak: The need to use 2P reserves. *Energy Policy, 35*(12), 6364-6382.

Berndes, G. (2006). The Contribution of Renewables to Society. In J. Dewulf & H. Van Langenhove (Eds.), *Renewables-Based Technology: Sustainability Assessment*: John Wiley & Sons.

Berndes, G., Hoogwijk, M., & van den Broek, R. (2003). The contribution of biomass in the future global energy supply: a review of 17 studies. *Biomass and Bioenergy, 25*, 1-28

Bernesson, S., Nilsson, D., & Hansson, P. A. (2004). A limited LCA comparino large- and smallscale production of rape methyl ester (RME) under Swedish conditions. *Biomass and Bioenergy, 26*, 545-559.

Bertalanffy, L. v. (1971). *General system theory : foundations, development, applications*. London: Allen Lane.

Bertani, R. (2003). What is geothermal Potential? . In I. G. Association (Ed.), *IGA News No. 53, pags. 1-3*

Bhatti, T. S., Bansal, R. C., & Kothon, D. P. (2004). *Small Hydro Power Systems*: Dhanpat Rai & Co.

Bishop, M., & Bishop, M. P. e. (2004). *Essential economics*. London: Economist in Association with Profile Books.

Blakers, A. (2004). Sustainable Energy. In J. Goldie, R. M. Douglas & B. Furnass (Eds.), *In search of sustainability* (pp. xii, 187 p.). Collingwood, Vic.: CSIRO Pub.

Bodger, P. S., & Baines, J. T. (1988). Dynamics of an energy-economic system subject to an energy substitution sequence. *Energy Systems and Policy; (USA); , 12*(3), Medium: X; Size: Pages: 167-178.

Bodger, P. S., Hayes, D. J., & Baines, J. T. (1989). The Dynamics of Primary Energy Substitution. *Technological Forecasting and Social Change, 36*(4), 425-439.

Boltzmann, L., & McGuinness, B. (1974). *Theoretical physics and philosophical problems : selected writings*. Dordrecht: Reidel.

Boustead, I., & Hancock, G. F. (1979). *Handbook of industrial energy analysis*. Chichester: Ellis Horwood.

BP (1999). *Statistical Review of World Energy*: British Petroleum.

BP (2008). *Statistical Review of World Energy*: British Petroleum.

Bracken, R., & Menninger, D. (2005). Oil Poster: Global Public Media.

Brandt, A. R. (2008). Converting oil shale to liquid fuels: Energy inputs and greenhouse gas emissions of the Shell in situ conversion process. *Environmental Science & Technology, 42*(19), 7489-7495.

Brandt, A. R. (2010) The Effects of Oil Depletion on the Energy Efficiency of Oil Production: Bottom-up Estimates from the California Oil Industry, *Entropy*, (in press).

Brooks, F. A., & Miller, W. (1963). Availability of Solar Energy. In A. M. Zarem (Ed.), *Introduction to the Utilization of Solar Energy*.

Brumfiel, G. (2009). Fusion dreams delayed. *Nature, 459*, 488-489.

Bullard, C. W. (1976). *Net energy analysis : handbook for combining process and input-output analysis, by Clark W. Bullard, Peter S. Penner [and] David A. Pilati*. Urbana, Ill.: Energy Research Group, Center for Advanced Computation, University of Illinois at Urbana-Champaign.

Bullard, C. W., & Herendeen, R. A. (1975). The energy cost of goods and services. *Energy Policy, 3*(4), 268-278.

Bullard, C. W. I. (1978). Energy and Employment Impacts of Policy Decisions. In M. Gilliland (Ed.), *Energy Analysis: A New Public Policy Tool*: Westview Press.

Cameron, J. (1979). *A review of long-term uranium resources, problems and requirements in relation to demand 1975-2025*. Paper presented at the First IIASA Conference on Energy Resources 1979.

Campbell, C. J. (1999). Oil Reserves and Depletion. *PESGB Newsletter, March*, 87-90.

Campbell, C. J., & Laherrere, J. H. (1998). The end of cheap oil. *Scientific American, 278*(3), 78.

Capra, F. (1997). *The web of life : a new synthesis of mind and matter*. London: Flamingo.

Cardone, M., Mazzoncini, M., Menini, S., Rocco, V., Senatore, A., Seggiani, M., et al. (2003). Brassica carinata as an alternative oil crop for the production of biodiesel in Italy: agronomic evaluation, fuel production by transesterification and characterization. *Biomass and Bioenergy, 25*(6), 623-636.

Carlson, I. C. G. (1979). *Energy analyses applied to an ocean thermal energy conversion (OTEC) system and an offshore windpower system (OWPS).*

Carter, A. J., Peet, J., & Baines, J. T. (1980). *Direct and indirect energy requirements of the New Zealand economy : an energy analysis of the 1971-72 inter-industry survey*. Christchurch: Dept. of Chemical Engineering, University of Canterbury.

Cavallo, A. J. (2002). Predicting the Peak in World Oil Production. *Natural Resources Research, 11*(3), 187-195.

Chandler, G. (1974). Energy: the changed and changing scene. In K. A. D. Inglis (Ed.), *Energy: from Surplus to Scarcity*: Applied Science

Chapman, P. F. (1977). Energy analysis of nuclear power stations. In J. A. G. Thomas (Ed.), *Energy Analysis*. IPC Science and Technology Press

Chapman, P. F., Leach, G., & Slesser, M. (1974). Energy Budgets .2. Energy Cost of Fuels. *Energy Policy, 2*(3), 231-243.

Chapman, P. F., & Mortimer, N. D. (1974). *Energy inputs and outputs of nuclear power*. Milton Keynes, England: Open University Energy Research Group Research Report.

Chapman, P. F., & Roberts, F. (1983). *Metal resources and energy*.

Checkland, P., & Scholes, J. (1990). *Soft System Methodology in Action*: John Wiley and Sons.

Chu, S., & Goldemberg, J. (2007). *Lighting the Way Towards a sustainable energy future* (No. ISBN 978-90-6984-531-9): InterAcademy Council.

Clerk-Maxwell, J. (1950, 31 August 1050). *The Times*.

Cleveland, C. J. (1987). Biophysical Economics - Historical-Perspective and Current Research Trends. *Ecological Modelling, 38*(1-2), 47-73.

Cleveland, C. J. (1991). Natural Resource Scarcity and Economic Growth Revisited: Economic and Biophysical Perspectives. In R. Costanza & L. Wainger (Eds.), *Ecological economics : the science and management of sustainability* (pp. 289-317). New York: Columbia University Press.

Cleveland, C. J. (2005). Net energy from the extraction of oil and gas in the United States. *Energy, 30*(5), 769-782.

Cleveland, C. J., Costanza, R., Hall, C. A. S., & Kaufmann, R. (1984). Energy and the U.S. Economy: A Biophysical Perspective. *Science, 225*(4665), 890-897.

Cleveland, C. J., Kaufmann, R. K., & Stern, D. I. (2000). Aggregation and the role of energy in the economy. *Ecological Economics, 32*, 301-317.

Cleveland, C. J., & Ruth, M. (1997). When, where, and by how much do biophysical limits constrain the economic process?: A survey of Nicholas Georgescu-Roegen's contribution to ecological economics. *Ecological Economics, 22*(3), 203-223.

Colander, D. C. (2004). *Economics* (5th ed.). Boston: McGraw-Hill/Irwin.

Cook, D. (2005). *The Natural Step: Towards a Sustainable Society* Green Books.

Cook, E. F. (1976). *Man, energy, society*. San Francisco: W. H. Freeman.

Costa Silva, A., & Barata Alves, F. (2005). *Partex Oil and Gas: A Vision of the World Market and the Role of Gas as the Future of Oil*: Partex Oil and Gas.

Costanza, R. (1978). *Energy Costs of Goods and Services in 1967 including Solar Energy Inputs and Labor and Government Service Feedbacks*: Center for Advanced Computation.

Costanza, R. (1980). Embodied Energy and Economic Valuation. *Science, 210*(4475), 1219-1224.

Costanza, R. (1994). Three general policies to achieve sustainability. In A. Jansson, M. Hammer & R. Costanza (Eds.), *Investing in Natural Capital* (pp. 1-21). Washington: Island Press.

Costanza, R., & Cleveland, C. J. (1983). *Ultimate recoverable hydrocarbons in Louisiana : a net energy approach*: Louisiana State University.

Costanza, R., & Cleveland, C. J. (2004). Value Theory and Energy *Encyclopedia of Energy* (pp. 337-346). New York: Elsevier.

Costanza, R., Leemans, R., Boumans, R. M. J., & Gaddis, E. (2007). Integrated Global Models. In R. Costanza, L. Graumlich & W. L. Steffen (Eds.), *Sustainability or collapse? : an integrated history and future of people on earth* (pp. xxii, 495 p.). Cambridge, Mass.: MIT Press in cooperation with Dahlem University Press.

Costello, R., & Chum, H. (1998). *Biomass, Bioenergy and Carbon Management.* Paper presented at the BioEnergy '98: Expanding BioEnergy Partnerships.

Cottrell, F. (1955). *Energy and society : the relation between energy, social change, and economic development*. N.Y.: McGraw-Hill.

Coughlin, K., & Fridley, D. (2008). *Physical Energy Accounting in California: A Case Study of Cellulosic Ethanol Production*: Lawrence Berkeley National Laboratory.

Czisch, G. (2004). Least Cost Electricity Supply for Europe and its Neighbours Entirely with Renewable Energies. *Geophysical Research Abstracts, 6*.

Daly, H. E. (1977). *Steady-state economics : the economics of biophysical equilibrium and moral growth*. San Francisco: W. H. Freeman.

Daly, H. E. (1985). The Circular Flow of Exchange Value and the Linear Throughput of Matter-Energy: A Case of Misplaced Concreteness. *Review of Social Economy, 43*(3), 279 - 297.

Daly, H. E. (1999). *Ecological economics and the ecology of economics : essays in criticism*. Cheltenham, UK ; Northampton, MA: E. Elgar.

Daly, H. E., & Farley, J. C. (2004). *Ecological economics : principles and applications*. Washington: Island Press.

Davenport, H. J. (1919). *The economics of enterprise*: The Macmillan Co.

David, P. A. (2007). Path dependence: a foundational concept for historical social science. *Cliometrica, 1*(2), 91-114.

Davidson, P. (1996). Reality and Economic Theory. *Journal of Post Keynesian Economics, 18*(4), 479-508.

de Vries, B. J. M., van Vuuren, D. P., & Hoogwijk, M. M. (2007). Renewable energy sources: Their global potential for the first-half of the 21st century at a global level: An integrated approach. *Energy Policy, 35*(4), 2590-2610.

Dempster, M. B. L. (1998). *A self-organizing systems perspective on planning for sustainability.* Unpublished Thesis (M E S)-University of Waterloo, 1998, University of Waterloo,, Waterloo, Ont.

Devezas, T., LePoire, D., Matias, J. C. O., & Silva, A. M. P. (2008). Energy scenarios: Toward a new energy paradigm. *Futures, 40*(1), 1-16.

Dewulf, J., & Van Langenhove, H. (2006). Exergy. In J. Dewulf & H. Van Langenhove (Eds.), *Renewables-Based Technology: Sustainability Assessment*: John Wiley & Sons.

Diamond, J. M. (2005). *Collapse : how societies choose to fail or succeed*. New York: Viking.

Dickson, M. H., & Fanelli, M. (2004). *What is Geothermal Energy?* : International Geothermal Association.

Dones, R., & Frischknecht, R. (1998). Life-cycle assessment of photovoltaic systems: results of Swiss studies on energy chains. *Progress in Photovoltaics: Research and Applications, 6*(2), 117-125.

Dong, X. B., Ulgiati, S., Yan, M. C., Zhang, X. S., & Gao, W. S. (2008). Energy and eMergy evaluation of bioethanol production from wheat in Henan Province, China. *Energy Policy, 36*(10), 3882-3892.

Duda, J. R., & Hemingway, E. L. (1976). *Basic estimated capital investment and operating costs for underground bituminous coal mines developed for longwall mining*. Morgantown, WV. (USA): Process Evaluation Group, Bureau of Mines.

Duncan, R. C., & Youngquist, W. (1999). Encircling the Peak of World Oil Production. *Natural Resources Research, 8*(3), 219-232.

Dupont, P. S., & Quesnay, F. o. (1768). *Physiocratie, ou constitution naturelle du Gouvernement le plus avantageux au genre humain. Recueil [of essays by F. Quesnay] publie\0301 par Du Pont, etc*: Leyde.

Edmonds, J., & Reilly, J. M. (1985). *Global Energy: Assessing the Future*: Oxford University Press.

Edmonds, J. A., Wise, M. A., Sands, R. D., Brown, R. A., & Kheshgi, H. (1996). *Agriculture, land use, and commercial biomass energy: A preliminary integrated analysis of the* *potential role of biomass energy for reducing future greenhouse related emissions*: Pacific Northwest National Laboratory.

EIA (1998). *International Energy Outlook*: US Dept. of Energy, Energy Information Administration.

EIA (2006). *International Energy Annual 2006*: Energy Information Administration.

EIA (2007). *Annual Energy Review 2007* (No. DOE/EIA-0384(2007)): Energy Information Administration.

EIA (2008). *International Energy Outlook* (No. DOE/EIA-0484): Energy Information Authority.

EIA (2010). *Electric Power Annual 2008* (No. DOE/EIA-0348(2008)): U.S. Energy Information Administration.

EPIA (2007). *Solar Generation IV - 2007*: European Photovoltaic Industry Association.

Etemad, B., & Luciani, J. (1991). *World energy production, 1800-1985 = Production mondiale d'énergie, 1800-1985*. Genève: Librairie Droz.

EWG (2009). *Wind Power in Context - A Clean Revolution in the Energy Sector*: Energy Watch Group.

Ezra, D. (1978). *Coal and Energy*: Benn.

Farrell, A. E.; Plevin, R. J.; Turner, B. T.; Jones, A. D.; O'Hare, M. & Kammen, D. (2006) Ethanol can contribute to energy and environmental goals, *Science* 311, 506

Fazzolare, R., & Smith, C. B. (1979). *Changing energy use futures : Second International Conference on Energy Use Management, held 22-26 October 1979, Los Angeles, California*. New York: Pergamon Press.

Fetter, S. (2000). Decarbonizing the Global Energy System. School of Public Affairs, University of Maryland.

Fettweis, G. (1979). *Contributions to the Assessment of World Coal Resources or Coal is not so Abundant*. Paper presented at the First IIASA Conference on Energy Resources 1979.

Field, C. B., Campbell, J. E., & Lobell, D. B. (2008). Biomass energy: the scale of the potential resource. *23*(2), 65-72.

Fischer, G., & Schrattenholzer, L. (2001). Global bioenergy potentials through 2050. *Biomass and Bioenergy, 20*, 151-159.

Fisher, J. C., & Pry, R. H. (1971). A simple substitution model of technological change. *Technological Forecasting and Social Change, 3*, 75-88.

Fishwick, P. A. (2007). The languages of Dynamic Systems Modeling. In P. A. Fishwick (Ed.), *Handbook of dynamic system modeling* (pp. 1 v. (various pagings)). Boca Raton, FL: Chapman & Hall/CRC.

Fleay, B. J. (2007). Natural Gas “Magic Pudding” or Depleting Resource: A dissertation on the state of Australian natural gas

Foran, B., & Crane, D. (1998). *The OzECCO Embodied Energy Model of Australia's Physical Economy*. Canberra: CSIRO Wildlife & Ecology.

Forrester, J. W. (1971). *World dynamics*. Cambridge, Mass.: Wright-Allen Press.

Forrester, J. W. (1972). *Principles of systems : text and workbook, chapters 1 through 10* (2d preliminary ed.). Cambridge, Mass.: Wright-Allen Press.

Fraas, A. P. (1982). *Engineering Evaluation of Energy Systems*: McGraw-Hill.

Frankl, P. (2001). *Life Cycle Assessment of Renewables: Present Issues, Future Outlook and Implications for the Calculation of External Costs*. Paper presented at the Externalities and Energy Policy: The Life Cycle Analysis Approach.

Freedman, D., Rothenberg, T., & Sutch, R. (1983). On Energy Policy Models. *Journal of Business & Economic Statistics, 1*(1), 24-32.

Fridleifsson, I. B. (2001). Geothermal energy for the benefit of the people. *Renewable and Sustainable Energy Reviews, 5*(3), 299-312.

Fridleifsson, I. B., Bertani, R., Huenges, E., Lund, J. W., Ragnarsson, A., & Rybach, L. (2008). *The possible role and contribution of geothermal energy to the mitigation of climate change* Paper presented at the IPCC Scoping Meeting on Renewable Energy Sources, Luebeck, Germany.

Frischknecht, R., Althaus, H. J., Bauer, C., Doka, G., Heck, T., Jungbluth, N., et al. (2007). The environmental relevance of capital goods in life cycle assessments of products and services. *International Journal of Life Cycle Assessment, 12*, 7-17.

Fthenakis, V., & Alsema, E. (2006). Photovoltaics energy payback times, greenhouse gas emissions and external costs: 2004 - early 2005 status. *Progress in Photovoltaics, 14*(3), 275-280.

Gagnon, L. (2008). Civilisation and energy payback. *Energy Policy, 36*(9), 3317-3322.

Gagnon, L., Belanger, C., & Uchiyama, Y. (2002). Life-cycle assessment of electricity generation options: The status of research in year 2001. *Energy Policy, 30*(14), 1267-1278.

Gagnon, N., Hall, C., & Brinker, L. (2009). A Preliminary Investigation of Energy Return on Energy Investment for Global Oil and Gas Production. *Energies, 2*(3), 490-503.

Gans, J., King, S., & Mankiw, N. G. (2003). *Principles of microeconomics* (2nd ed.). Southbank, Vic.: Thomson.

Gately, M. (2007). The EROI of U.S. offshore energy extraction: A net energy analysis of the Gulf of Mexico. *Ecological Economics, 63*(2-3), 355-364.

Georgescu-Roegen, N. (1974). *The Entropy Law and the economic process*. Cambridge, Mass.: Harvard University Press.

Georgescu-Roegen, N. (1975). Energy and Economic Myths. *Southern Economic Journal, 41*(3), 347-381.

Gever, J., Kaufmann, R., Skole, D., & Vorosmarty, C. (1991). *Beyond oil : the threat to food and fuel in the coming decades* (3rd ed.). Niwot, Colo: University Press of Colorado.

Giampietro, M., & Ulgiati, S. (2005). Integrated assessment of large-scale biofuels. *Critical Reviews in Plant Sciences, 24*(20), 365-384.

Giampietro, M., Ulgiati, S., & Pimentel, D. (1997). Feasibility of large-scale biofuel production: does an enlargement of scale change the picture? *BioScience, 47*(9), 587-600.

Gilland, B. (1995). World Population, Economic Growth, and Energy Demand, 1990-2100: A Review of Projections. *Population and Development Review, 21*(3), 507-539.

Gilliland, M. W. (1975). Energy Analysis and Public Policy. *Science, 189*(4208), 1051-1056.

Glaser, J. (2006). Corporate responsibility and the triple bottom line. *Clean Technologies and Environmental Policy, 8*(4), 225-228.

Goldemberg, J., Johansson, T., Reddy, A. K. N., & Williams, R. H. (1988). *Energy for a Sustainable World*: John Wiley and Sons.

Goldsmith, E. (1972). *Blueprint for survival*. Boston: Houghton Mifflin.

Goodstein, E. S. (2008). *Economics and the environment* (5th ed.). Hoboken, NJ: John Wiley & Sons.

Graßl, H., Kokott, J., Kulessa, M., Luther, J., Nuscheler, F., Sauerborn, R., et al. (2004). *World in Transition: Towards Sustainable Energy Systems*: German Advisory Council on Global Change (WBGU).

Grenon, M. (1977). Global Energy Resources. *Annual Review of Energy, 2*(1), 67-94.

Grenon, M. (1978). *On Fossil Fuel Reserves and Resources*: IIASA.

Grenon, M. (1979). *Resource Studies in the Energy Project of IIASA*. Paper presented at the First IIASA Conference on Energy Resources 1977.

Griffin, J. M. (1981). Engineering and Econometric Interpretations of Energy-Capital Complementarity: Comment. *The American Economic Review, 71*(5), 1100-1104.

Griffin, J. M., & Gregory, P. R. (1976). An Intercountry Translog Model of Energy Substitution Responses. *The American Economic Review, 66*(5), 845-857.

Gross, R., Leach, M., & Bauen, A. (2003). Progress in renewable energy. *Environment International, 29*(1), 105-122.

Grubb, M., & Meyer, N. I. (1993). Wind Energy: Resources, Systems and Regional Strategies. In T. B. Johansson, L. Burnham & A. K. N. Reddy (Eds.), *Renewable energy: sources for fuels and electricity*: Island Press.

Grübler, A. (1998). *Technology and global change*. Cambridge: Cambridge University Press.

Grübler, A., Jefferson, M., & Nakicenovic, N. (1996). Global energy perspectives: A summary of the joint study by the international institute for applied systems analysis and world energy council. *Technological Forecasting and Social Change, 51*(3), 237-264.

Gunderson, L. H., & Holling, C. S. (2001). *Panarchy : understanding transformations in human and natural systems*. Washington: Island Press.

Gunderson, L. H., & Pritchard, L. (2002). *Resilience and the behavior of large-scale systems*. Washington, DC [u.a.: Island Press.

GWEC (2009). *Press Release: Table and Statistics 2008*: Global Wind Energy Council.

HaciseferoÄŸullari, H., AcaroÄŸlu, M., & Gezer, Ä. b. m. (2003). Determination of the Energy Balance of the Sugar Beet Plant. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 25*(1), 15 - 22.

Haegele, J., Steward, B., Visser, E., Martinez, M., Deal, C., Oliveira, D., et al. (2007). *Modeling a Renewable Energy System to Meet University Energy Needs and Promote Regional Sustainable Development*

Iowa State University

Federal University of Viçosa.

Häfele, W. (1979). World Regional Energy Modelling. In R. Mabro (Ed.), *World Energy: Issues and Policy*: Oxford University Press.

Häfele, W. (1981). *Energy in a Finite World: A Global Systems Analysis* (Vol. 2): Ballinger.

Hall, A. D. (1962). *A methodology for systems engineering*. N.Y.: Van Nostrand Reinhold.

Hall, C., Balogh, S., & Murphy, D. (2009). What is the Minimum EROI that a Sustainable Society Must Have? *Energies, 2*(1), 25-47.

Hall, C. A. S. (2004). The Myth of Sustainable Development: Personal Reflections on Energy, its Relation to Neoclassical Economics, and Stanley Jevons. *Journal of Energy Resources Technology, 126*(2), 85-89.

Hall, C. A. S., Cleveland, C. J., & Kaufman, R. (1986). *Energy and Resource Quality: The Ecology of the Economic Process*: John Wiley & Sons.

Hall, C. A. S., Cleveland, C. J., & Kaufman, R. (Eds.). (2008) Encyclopedia of Earth. Washington D.C.

Hall, C. A. S., & Day, J. W. (1990). *Ecosystem modeling in theory and practice : an introduction with case histories*. Niwot, Colo: University Press of Colorado.

Hall, D. O. (1997). Biomass energy in industrialised countries--a view of the future. *Forest Ecology and Management, 91*(1), 17-45.

Hall, D. O., Rosillo-Calle, F., Williams, R. H., & Woods, J. (1993). Biomass for energy: supply prospects. In J. T.B.J., H. Kelly, A. K. N. Reddy & R. Williams (Eds.), *Renewable fuels and electricity for a growing world economy: defining and achieving the potential*. Washington, DC: Island Press.

Hallock, J. J. L., Tharakan, P. J., Hall, C. A. S., Jefferson, M., & Wu, W. (2004). Forecasting the limits to the availability and diversity of global conventional oil supply. *Energy, 29*(11), 1673-1696.

Halloran, D. (2007). EROI of Geothermal Energy Production. SUNY.

Hamilton, J. D. (1983). Oil and the Macroeconomy since World War II. *The Journal of Political Economy, 91*(2), 228-248.

Hamilton, L. D., Goldstein, G. A., Lee, J., Marcuse, W., Morris, S. C., Manne, A. S., et al. (1992). *MARKAL-MACRO: An overview* (No. BNL-48377; Other: ON: DE93016554 United States10.2172/6278632Other: ON: DE93016554Mon Jun 30 08:37:34 EDT 2008OSTI; NTIS; GPO Dep.BNL; EDB-93-104591English).

Hammerschlag, R. (2006). Ethanol's Energy Return on Investment: A Survey of the Literature 1990-Present. *Environ. Sci. Technol., 40*, 1744-1750.

Hammons, T. J. (1993). Tidal power. *Proceedings of the IEEE, 81*(3), 419-433.

Hannon, B. (1975). Energy Conservation and Consumer. *Science, 189*(4197), 95-102.

Hannon, B. (1977). Energy, growth, and altruism. In D. L. Meadows (Ed.), *Alternatives to growth-I : a search for sustainable futures : papers adapted from entries to the 1975 George and Cynthia Mitchell Prize and from presentations before the 1975 Alternatives to Growth Conference, held at the Woodlands, Texas* (pp. 79-100). Cambridge, Mass.: Ballinger Pub. Co.

Hannon, B. M., & Ruth, M. (2000). *Dynamic modeling* (2nd ed.). New York: Springer.

He, X. M., Cheng, S. W., & Wang, S. Y. (2009, Jun 21-26). *A Study of Crude Oil Price Behavior Based on Fictitious Economy Theory*. Paper presented at the 20th

International Conference on Multiple Criteria Decision Making, Chengdu, PEOPLES R CHINA.

Heller, M. C., Keoleian, G. A., Mann, M. K., & Volk, T. A. (2004). Life cycle energy and environmental benefits of generating electricity from willow biomass. *Renewable Energy, 29*(7), 1023-1042.

Heller, M. C., Keoleian, G. A., & Volk, T. A. (2003). Life cycle assessment of a willow bioenergy cropping system. *Biomass and Bioenergy, 25*(2), 147-165.

Herendeen, R. A. (1979). *Energy analysis of geothermal energy supply systems. Second quarterly report* (No. COO-5085-2). United States.

Herendeen, R. A., & Plant, R. L. (1981). Energy Analysis of 4 Geothermal Technologies. *Energy, 6*(1), 73-82.

Higman, C.; van der Burgt, M. (2008) *Gasification*, Gulf Professional Publishing.

Hill, J., Nelson, E., Tilman, D., Polasky, S., & Tiffany, D. (2006). Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *Proceedings of the National Academy of Sciences of the United States of America, 103*(30), 11206-11210.

Hill, R., O'Keefe, P., & Snape, C. (1995). *The Future of Energy*: Earthscan.

Holling, C. S. (2001). Understanding the Complexity of Economic, Ecological, and Social Systems. *Ecosystems, 4*(5), 390-405.

Holmgren, D. (2002). *Permaculture : principles and pathways beyond sustainability*. Hepburn, Vic.: Holmgren Design Services.

Hondo, H. (2005). Life cycle GHG emission analysis of power generation systems: Japanese case. *Energy, 30*(11-12), 2042-2056.

Hoogwijk, M., de Vries, B., & Turkenburg, W. (2004). Assessment of the Global and regional geographical, technical and economic potential of onshore wind energy. *Energy Economics, 26,* 889- 919.

Hoogwijk, M., Faaij, A., Eickhout, B., de Vries, B., & Turkenburg, W. (2005). Potential of biomass energy out to 2100, for four IPCC SRES land-use scenarios. *Biomass and Bioenergy, 29*, 225-257.

Hoogwijk, M. M. (2004). *On the Global and Regional Potential of Renewable Energy Sources.* Universiteit Utrecht, Utrecht.

Hopkins, R. (2008). *The Transition Handbook: From Oil Dependence to Local Resiliance*: Green Books

Hopkinson, C. S., & Day, J. W. (1980). Net Energy Analysis of Alcohol Production from Sugarcane. *Science, 207*(4428), 303-304.

Horlacher, H.-B. (2002). *Globale Potenziale der Wasserkraft - Expertise for the WBGU Report 'World in Transition: Towards Sustainable Energy Systems'*: WBGU.

Hotelling, H. (1931). The Economics of Exhaustible Resources. *The Journal of Political Economy, 39*(2), 137-175.

Hounam, I. (1979). *STER - A Global Energy Supply Model*. Paper presented at the Energy systems analysis : proceedings of the International Conference, held in Dublin, Ireland, 9-11 October 1979.

Huang, J. J. (2007). *Life Cycle Analysis of Hybrid Poplar Trees for Cellulosic Ethanol.* Massachusetts Institute of Technology, Boston.

Hubbert, M. K. (1956). Nuclear Energy and the Fossil Fuels *Drilling and Production Practice* (Vol. 95): American Petroleum Institute, Shell Development Co.

IAEA (2008). PRIS Database. Retrieved 16/04/2008, from International Atomic Energy Agency:

Icerman, L. (1980). Net Energy-Production History of the Geysers Geothermal Project. *Energy, 5*(1), 29-33.

ICOLD (1998). *World register of dams 1998* (No. 2868120024). Paris International Commission on Large Dams.

IEA (1998). *World Energy Outlook*: International Energy Agency.

IEA (2000). *Experience Curves for Energy Technology Policy*. Paris: OECD/IEA.

IEA (2004). *Biofuels for transport : an international perspective*. Paris, France: International Energy Agency.

IEA (2006). *Energy Technology Perspectives: Scenarios and Strategies to 2050*: International Energy Agency.

IEA (2007a). A Hybrid Modelling Framework to Incorporate Expert Judgment in Integrated Economic and Energy Models – The IEA WEM-ECO model: International Energy Agency.

IEA (2007b). *Renewables in Global Energy Supply*: International Energy Agency.

IEA (2008a). personal communication. In R. Quadrelli (Ed.).

IEA (2008b). *Trends in photovoltaic applications: Survey report of selected IEA countries between 1992 and 2007*: IEA Photovoltaic Power Systems Programme.

IEA (2008c). *World Energy Outlook 2008*: International Energy Agency.

IEA Bioenergy (2000). *Greenhouse Gas Balances of Bioenergy Systems.* Paper presented at the Bioenergy for mitigation of CO2 emissions: the power, transportation and industrial sectors, Gatlinburg, Tennessee, USA.

IFIAS (1974) *Energy Analysis Workshop on Methodology and Conventions, Report 6,* International Federation of Institutes for Advanced Study, Stockholm: Sweden.

IFIAS (1976) *Energy analysis and economics, Report 6,* International Federation of Institutes for Advanced Study.

Illum, K. (2005). IEA Oil Projections Revisited. ECO Consult, Denmark.

IOR (2005). List of common conversion factors Retrieved 11th February, 2010, from http://www.ior.com.au/ecflist.html

IPCC (2001). *Technological and Economic Potential of Greenhouse Gas Emissions Reduction*: Intergovernmental Panel on Climate Change.

IPCC, Moomaw, W., Moreira, J. R., Blok, K., Greene, D. L., Gregory, K., et al. (2001). *Technological and Economic Potential of Greenhouse Gas Emissions Reduction*. London: Intergovernmental Panel on Climate Change.

Ismayilova, R. M. (2007). *Power from Woody Residues and Agricultural Crops in East Texas.* Texas A & M University.

Jaccard, M. K. (2005). *Sustainable fossil fuels : the unusual suspect in the quest for clean and enduring energy*. Cambridge, UK ; New York: Cambridge University Press.

Jackson, T. (1992). Summary paper for the renewables series. *Energy Policy, 20*(9), 861-883.

Jacobson, M. Z. (2008). A Renewable Energy Solution to Global Warming. Department of Civil & Environmental Engineering, Stanford University.

Janulis, P. (2004). Reduction of energy consumption in biodiesel fuel life cycle. *Renewable Energy, 29*(6), 861-871.

Jebaraj, S., & Iniyan, S. (2006). A review of energy models. *Renewable & Sustainable Energy Reviews, 10*(4), 281-311.

Johansson, B. (1997). *Renewable Energy in Energy-Efficient, Low-Pollution Systems.* Unpublished Doctoral Dissertation, Lund University.

Johansson, T. B., & Burnham, L. (1993). *Renewable energy : sources for fuels and electricity*. Washington, D.C: Island Press.

Johansson, T. B., McCormick, K., Neij, L., & Turkenburg, W. (2004). *The Potentials of Renewable Energy: Thematic Background Paper*. Paper presented at the International Conference for Renewable Energies.

Johansson, T. B. J., Kelly, H., Reddy, A. K. N., & Williams, R. (1993a). A renewables-intensive global energy scenario. In J. T.B.J., H. Kelly, A. K. N. Reddy & R. Williams (Eds.), *Renewable fuels and electricity for a growing world economy: defining and achieving the potential*. Washington, DC: Island Press.

Johansson, T. B. J., Kelly, H., Reddy, A. K. N., & Williams, R. (1993b). Renewables for fuels and electricity. In T. B. J. Johansson, H. Kelly, A. K. N. Reddy & R. Williams (Eds.), *Renewable fuels and electricity for a growing world economy: defining and achieving the potential*. Washington, DC: Island Press.

Jones, J. C. (2007). Synthesis gas derived fuels and carbon neutrality. *Fuel, 86*, 2021.

Junginger, M.; Faaij, A.; Turkenburg, W.C. (2005) Global experience curves for wind farms. *Energy Policy*, *33*(2), 133–150.

Kallivroussis, L., Natsis, A., & Papadakis, G. (2002). RD--Rural Development: The Energy Balance of Sunflower Production for Biodiesel in Greece. *Biosystems Engineering, 81*(3), 347-354.

Kannan, R., Leong, K. C., Osman, R., Ho, H. K., & Tso, C. P. (2006). Life cycle assessment study of solar PV systems: An example of a 2.7 kW(p) distributed solar PV system in Singapore. *Solar Energy, 80*(5), 555-563.

Keoleian, G. A., & Lewis, G. M. (2003). Modeling the life cycle energy and environmental performance of amorphous silicon BIPV roofing in the US. *Renewable Energy, 28*(2), 271-293.

Keoleian, G. A., & Volk, T. A. (2005). Renewable energy from willow biomass crops: Life cycle energy, environmental and economic performance. *Critical Reviews in Plant Sciences, 24*(5-6), 385-406.

Keynes, J. M. (1936). The general theory. *London, New York*.

Khan, A. M. (1987). Techno-economic aspects of non-renewable energy resources. In H. H. Rogner, A. M. Khan & G. Furlan (Eds.), *Economics, Modelling, Planning and Management of Energy*: World Scientific.

Khisty, C. J., & Mohammadi, J. (2001). *Fundamentals of systems engineering : with economics, probability, and statistics*. Upper Saddle River, NJ: Prentice Hall.

King, J., & Slesser, M. (1995). Can the World Make the Transition to a Sustainable Economy Driven by Solar-Energy. *International Journal of Environment and Pollution, 5*(1), 14-29.

King, P. (1980). Improved Extraction of Coal. *Journal of the South African Institute of Mining and Metallurgy, Jan*.

Klett, T. R., Gautier, D. L., & Ahibrandt, T. S. (2007). *An Evaluation of the World Petroleum Assessment 2000: Supporting Data*.

Knapp, K., & Jester, T. (2001). Empirical investigation of the energy payback time for photovoltaic modules. *Solar Energy, 71*(3), 165-172.

Kokesh, A. (2006). Nuclear Energy: Fuel of the Future? In J. E. Morhardt (Ed.), *Research in Natural Resources Management: The Roberts Environmental Center 2006 Guide*: The Roberts Environmental Center Press.

Korpela, S. A. (2002). *Oil Depletion in the United States and the World*: Ohio State University.

Kowalik, Z. (2004). Tide distribution and tapping into tidal energy. *Oceanologia, 46*(3), 291-331.

Kubiszewski, I., & Cleveland, C. J. (Eds.). (2008) Encyclopedia of Earth.

Laherrere, J. (1998). *Evolution des reserves mondiales d'hydrocarbures*. Paper presented at the SPE France.

Laherrere, J. (2001). *Estimates of Oil Reserves*. Paper presented at the EMF/IEA/IEW meeting IIASA, .

Laherrere, J., & Cutler, J. C. (2004). Oil and Natural Gas Resource Assessment: Production Growth Cycle Models *Encyclopedia of Energy* (pp. 617-631). New York: Elsevier.

Lashof, D. A., & Tirpak, D. A. (1990). *Policy options for stabilizing global climate*. New York, Washington, Philadelphia, London: Hemisphere Publishing Corporation.

Lavigne, A., & Powers, S. E. (2007). Evaluating fuel ethanol feedstocks from energy policy perspective: A comparative energy assessment of corn and corn stover. *Energy Policy, 35*(11), 5918-5930.

Lazarus, M., Greber, L., Hall, J., Bartels, C., Bernow, S., Hansen, E., et al. (1993). *Towards a Fossil Free Energy Future: A Technical Analysis for Greenpeace International*: Stockholm Environmental Institute.

Leach, G. (1976). *Energy and Food Production*: IPC Science and Technology Press.

Leach, G. (1977). Net energy analysis - is it any good? In J. A. G. Thomas (Ed.), *Energy Analysis*: IPC Science and Technology Press.

Leemans, R., van Amstel, A., Battjes, C., Kreileman, E., & Toet, S. (1996). The land cover and carbon cycle consequences of large-scale utilizations of biomass as an energy source. *Global Environmental Change, 6*(4), 335-357.

Leggett, J. (2005). *Half gone: Oil, Gas, Hot Air & the Global Energy Crisis*: Portobello.

Leutz, R., Ackermann, T., Suzuki, A., Akisawa, A., & Kashiwagi, T. (2001). *Technical offshore wind energy potentials around the globe*. Paper presented at the European Wind Energy Conference and Exhibition.

Li, M. (2007). Capitalism with Zero Profit Rate?: Limits to Growth and the Law of the Tendency for the Rate of Profit to Fall. University of Utah, Department of Economics.

Lidsky, L. M., & Miller, M. M. (2002). Nuclear Power and Energy Security: A Revised Strategy for Japan. *Science & Global Security: The Technical Basis for Arms Control, Disarmament, and Nonproliferation Initiatives, 10*(2), 127 - 150.

Lietaer, B. (2001). *The Future of Money: Creating New Wealth, Work and a Wiser World*: Century.

Lightfoot, H. D., & Green, C. (2002). *An Assessment of IPCC Working Group III Findings in Climate Change 2001: Mitigation of the Potential Contribution of Renewable Energies to Atmospheric Carbon Dioxide Stabilization*: McGill Centre for Climate and Global Change Research, Canada.

Lindenberger, D., & Kummel, R. (2002). Energy-Dependent Production Functions and the Optimization Model "PRISE" of Price-Induced Sectoral Evolution. *Int.J. Applied Thermodynamics, 5*(3), 101-107.

Lindmayer, J., Anderson, J., Clifford, A., Lafky, W., Scheinine, A., Wihl, M., et al. (1977). *Solar Breeder: energy payback time for silicon photovoltaic systems - First quarterly report*. Rockville, MD (USA): Solarex Corp.

Liska, A. J., Yang, H. S., Bremer, V. R., Klopfenstein, T. J., Walters, D. T., Erickson, G. E., et al. (2009). Improvements in Life Cycle Energy Efficiency and Greenhouse Gas Emissions of Corn-Ethanol. *Journal of Industrial Ecology, 13*(1), 58-74.

Liu, Z., Koerwer, J., Nemoto, J., & Imura, H. (2008). Physical energy cost serves as the "invisible hand" governing economic valuation: Direct evidence from biogeochemical data and the U.S. metal market. *Ecological Economics*, *67*(1), 104-108.

Lloyd, B. & Forest, A. S. (2010) The transition to renewables: Can PV provide an answer to the peak oil and climate change challenges?, *Energy Policy, 38*(11), 7378-7394.

Lorenz, D., & Morris, D. (1995). *How Much Energy Does It Take to Make a Gallon of Ethanol?* : Institute for Local-Self Reliance (ILSR).

Lovins, A. B. (2004). *Winning the oil endgame : innovation for profit, jobs and security*. London: Earthscan.

Lund, C., & Biswas, W. (2008). A Review of the Application of Lifecycle Analysis to Renewable Energy Systems. *Bulletin of Science Technology Society, 28*(3), 200-209.

Ma, T., Grubler, A., Nakicenovic, N., & Arthur, W. B. (2008). *Technologies as Agents of Change: A Simulation Model of the Evolving Complexity of the Global Energy System*: IIASA.

MacKay, D. J. C. (2008). *Sustainable Energy* - *without the hot air*: UIT Cambridge.

MacKenzie, J. (1998). Oil as a finite resource. *Natural Resources Research, 7*(2), 97-100.

Malthus, T. R., & Appleman, P. (1976). *An essay on the principle of population : text, sources and background, criticism. Edited by Philip Appleman*. N.Y.: Norton.

Mann, M. K., & Spath, P. L. (1999). *The Net CO2 Emissions and Energy Balances of Biomass and Coal-Fired Power Systems*. Paper presented at the 4th Biomass Conference of the Americas: A Growth Opportunity in Green Energy and Value-Added Products.

Mann, M. K., & Spath, P. L. (2001). A life cycle assessment of biomass cofiring in a coal-fired power plant. *Clean Technologies and Environmental Policy, 3*(2), 81-91.

Manne, A. S., & Wene, C. O. (1992). *MARKAL-MACRO: A linked model for energy-economy analysis* (No. BNL--47161; Other: ON: DE92009378 United States10.2172/10131857Other: ON: DE92009378Thu Jun 19 07:53:45 EDT 2008OSTI; NTIS; INIS; GPO Dep.BNL; SCA: 990200; 290100; 290301; SN: 92000694665English).

Marchetti, C. (1977). Primary energy substitution models: On the interaction between energy and society. *Technological Forecasting and Social Change, 10*(4), 345-356.

Marchetti, C., Nakicenovic, N., Peterka, V., & Fleck, F. (1978). *The Dynamics of Energy Systems and the Logistic Substitution Model*: IIASA.

Marshall, J. D., & Toffel, M. W. (2005). Framing the Elusive Concept of Sustainability: A Sustainability Hierarchy. *Environmental Science and Technology, 39*(3), 673-682.

Martinez, E., Sanz, F., Pellegrini, S., Jimenez, E., & Blanco, J. (2009). Life-cycle assessment of a 2-MW rated power wind turbine: CML method. *International Journal of Life Cycle Assessment, 14*(1), 52-63.

Martins, J. (2005). The impact of the use of energy sources on the quality of life of poor communities. *Social Indicators Research, 72*(3), 373-402.

Martinsen, D., & Krey, V. (2008). Compromises in energy policy--Using fuzzy optimization in an energy systems model. *Energy Policy, 36*(8), 2983-2994.

Masera Barbara, D., & Omar, R. (2000). From linear fuel switching to multiple cooking strategies: a critique and alternative to the energy ladder model. *World Development, 28*(12), 2083-2103.

Mason, J. E., Fthenakis, V. M., Hansen, T., & Kim, H. C. (2006). Energy payback and life-cycle CO2 emissions of the BOS in an optimized 3.5 MW PV installation. *Progress in Photovoltaics, 14*(2), 179-190.

Masters, C. D. (1993). US Geological Survey Petroleum Resource Assessment Procedures. *AAPG Bulletin-American Association of Petroleum Geologists, 77*, 452.

Mathur, J. (2001). *Development of a modified dynamic energy and greenhouse gas reduction planning approach through the case of Indian power sector.* Universität GH Essen.

Mathur, J., & Bansal, N. (1999). Energy analysis of solar water heating systems in india. *The International Journal of Life Cycle Assessment, 4*(2), 113-116.

Mathur, J., & Bansal, N. K. (2001). Analysis of Selected Renewable Energy Options for India. *Energy Sources 23*, 877-888.

Mathur, J., Bansal, N. K., & Wagner, H.-J. (2002). Energy and Environmental Correlation for Renewable Energy Systems in India. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 24*(1), 19-26.

Matthews, R. W. (2001). Modelling of energy and carbon budgets of wood fuel coppice systems. *Biomass & Bioenergy, 21*(1), 1-19.

Maturana, H., & Varela, F. (1972). Autopoiesis: The Organization of the Living. Editorial Universitaria.

Maturana, H. R. (1975). Organization of Living - Theory of Living Organization. *International Journal of Man-Machine Studies, 7*(3), 313-332.

Mayumi, K. (1999). Embodied energy analysis, Sraffa's analysis, Georgescu-Roegen's flow-fund model and viability of solar technology. In K. Mayumi & J. M. Gowdy (Eds.), *Bioeconomics and sustainability : essays in honor of Nicholas Georgescu-Roegen* (pp. xviii, 417 p.). Cheltenham, UK ; Northampton, MA, USA: E. Elgar.

McLaughlin, S. B., & Walsh, M. E. (1998). Evaluating environmental consequences of producing herbaceous crops for bioenergy. *Biomass and Bioenergy, 14*(4), 317-324.

McMullen, J. T., Morgan, R., & Murray, R. B. (1977). *Energy Resources*: Resource and Environmental Science Series.

Meadows, D. H., Meadows, D. L., & Randers, J. (1992). *Beyond the limits : confronting global collapse, envisioning a sustainable future*. Post Mills, Vt: Chelsea Green Pub.

Meadows, D. H., Meadows, D. L., Randers, J., & Behrens III, W. W. (1972). *The Limits to Growth*. New York: Universe Books.

Meadows, D. L. (2007). Evaluating Past Forecasts: Reflections on One Critique of *The Limits to Growth*. In R. Costanza, L. Graumlich & W. L. Steffen (Eds.), *Sustainability or collapse? : an integrated history and future of people on earth* (pp. xxii, 495 p.). Cambridge, Mass.: MIT Press in cooperation with Dahlem University Press.

Meier, P. J. (2002). *Life Cycle Assessment of Electricity Generation Systems and Applications for Climate Change Policy Analysis.* University of Wisconsin, Madison, WI, USA.

Meier, P. J., & Kulcinski, G. L. (2002). *Life-Cycle Energy Requirements and Greenhouse Gas Emissions for Building-Integrated Photovoltaics*: Energy Center of Wisconsin.

Meng, Q. Y., & Bentley, R. W. (2008). Global oil peaking: Responding to the case for `abundant supplies of oil'. *Energy, 33*(8), 1179-1184.

Messner, S., & Schrattenholzer, L. (2000). MESSAGE-MACRO: linking an energy supply model with a macroeconomic module and solving it iteratively. *Energy, 25*(3), 267-282.

Messner, S., & Strubegger, M. (1986). *First Order Effects of a Nuclear Moratorium in Central Europe*: IIASA.

Messner, S., & Strubegger, M. (1995). *User's Guide for MESSAGE III*: IIASA.

Mighty River Power (2007). Arapuni Retrieved 10th February, 2010, from http://www.mightyriverpower.co.nz/Generation/AboutUs/HydroStations/Arapuni/Technical.aspx

Mirabeau, V. d. R. M. d. (1763). *Philosophie rurale, ou, Economie generale et politique de l'agriculture*. Amsterdam: Les Libraires associes.

MIT (1977). *Energy: Global Prospects 1985 - 2000: Report of the Workshop on Alternative Energy Strategies*: McGraw-Hill.

Moreira, J. R. (2002). *Can Renewable Energy Make Important Contribution to GHG Atmospheric Stabilization?* Paper presented at the LAMNET Third Project Workshop.

Moreira, J. X. C. (2006). Global Biomass Energy Potential. *Mitigation and Adaptation Strategies for Global Change, 11*(2), 313-333.

Morgan, M. S., & Morrison, M. (1999). *Models as mediators : perspectives on natural and social science*. Cambridge: Cambridge University Press.

Mudd, G. M. (2007). An analysis of historic production trends in Australian base metal mining. *Ore Geology Reviews, 32*(1-2), 227-261.

Nakicenovic, N., Grübler, A., & McDonald, A. (1998). *Global energy perspectives*: International Institute for Applied Systems Analysis/World Energy Council.

Nakicenovic, N., & Riahi, K. (2002). *An Assessment of Technological Change Across Selected Energy Scenarios*: IIASA/WEC.

Nakicenovic, N., & Swart, R. (2000). *Special Report on Emissions Scenarios*. Cambridge: Intergovernmental Panel on Climate Change (IPCC).

Nathwani, J. S., Siddal, E., & Lind, N. C. (1992). *Energy for 300 years: Benefits and Risks*: Institute for Risk Research.

NEO (2010). Ethanol and Unleaded Gasoline Average Rack Prices Retrieved 12th April 2010, from http://www.neo.ne.gov/statshtml/66.html

Nitsch, J. (1994). The Global Potential of Renewable Energy Sources. *Structural Engineering International*, *4*(2), 72-75.

Nordhaus, W. D. (1973). Allocation of Energy Resources. [Article]. *Brookings Papers on Economic Activity*(3), 529-570.

Nordhaus, W. D. (1974). Resources as a Constraint on Growth. *The American Economic Review*, *64*(2), 22-26.

Nordhaus, W. D. (1992). The'DICE'Model: Background and Structure of a Dynamic Integrated Climate-Economy Model of the Economics of Global Warming. *Cowles Foundation Discussion Papers*.

Norgaard, R. B. (1990). Economic indicators of resource scarcity: A critical essay. *Journal of Environmental Economics and Management, 19*(1), 19-25.

NREL (2000). *Photovoltaics: Energy for the New Millenium*. Golden, Colorado: National Renewable Energy Laboratory.

NREL (2009). Concentrating Solar Power Projects. from National Renewable Energy Laboratory: http://www.nrel.gov/csp/solarpaces/

NREL (2010a) *Western Wind Dataset*, National Renewable Energy Laboratory.

NREL (2010b) *National Solar Radiation Database*, National Renewable Energy Laboratory.

Obersteiner, M., Alexandrov, G., Benítez, P., McCallum, I., Kraxner, F., Riahi, K., et al. (2006). Global Supply of Biomass for Energy and Carbon Sequestration from Afforestation/Reforestation Activities. *Mitigation and Adaptation Strategies for Global Change, 11*(5), 1003-1021.

Odell, P. R. (1973). The Future of Oil: A Rejoinder. *The Geographical Journal, 139*(3), 436-454.

Odell, P. R. (2001). *Oil and Gas: Global Issues*: Multi-Science Publishing.

Odum, H. T. (1975). *Energy Analysis and Net Energy*. Paper presented at the NSF Workshop on Net Energy.

Odum, H. T. (1977). Energy, value, and money. In C. A. S. Hall & J. W. Day (Eds.), *Ecosystem modeling in theory and practice : an introduction with case histories* (pp. 174-196). Niwot, Colo: University Press of Colorado.

Odum, H. T. (1983). *Systems ecology : an introduction*. New York: Wiley.

Odum, H. T. (1996). *Environmental accounting : EMERGY and environmental decision making*. New York: Wiley.

OECD (2001). *OECD environmental strategy for the first decade of the 21st century*. Paris: Organisation for Economic Co-operation and Development (OECD).

OECD/IEA (2009). World Energy Model - Methodology and Assumptions: International Energy Agency.

Pacca, S., Sivaraman, D., & Keoleian, G. A. (2007). Parameters affecting the life cycle performance of PV technologies and systems. *Energy Policy, 35*(6), 3316-3326.

Page, N. J., & Creasey, S. C. (1975). Ore Grade, Metal Production, and Energy. *Journal of Research of the Us Geological Survey, 3*(1), 9-13.

Pan, F., Han, H. S., Johnson, L. R., & Elliot, W. J. (2008). Net energy output from harvesting small-diameter trees using a mechanized system. *Forest Products Journal, 58*(1-2), 25-30.

Parker, M. J. (1979). Coal: Recent Developments and Problems of Supplies. In R. Mabro (Ed.), *World Energy: Issues and Policy*: Oxford University Press.

Parkins, W. E. (2006). ENERGY: Fusion Power: Will It Ever Come? *Science, 311*(5766), 1380-.

Patel, M. R. (2006). *Wind and solar power systems : design, analysis, and operation* (2nd ed.). Boca Raton, FL: Taylor & Francis.

PCE (2002). *Creating our Future: Sustainable Development for New Zealand*: Parliamentary Commissioner for the Environment, Te Kaitiaki Taiao a Te Whare Päremata.

Peckham, R. J., & Klitz, J. K. (1979). *Energy Requirements for North Sea Oil by Secondary and Tertiary Production Methods*. Laxenburg, Austria: International Institute for Applied Systems Analysis

Peet, J. (1992). *Energy and the ecological economics of sustainability*. Washington, D.C: Island Press.

Peet, N. J. (1986). *Energy Analysis: A Review of Theory and Applications*: New Zealand Energy Research and Development Committee.

Pehnt, M., Bubenzer, A., & Räuber, A. (2002). Lifecycle assessment of Photovoltaic systems - trying to fight deep-seated prejudices. In A. Bubenzer & J. Luther (Eds.), *Photovoltaics Guidebook for Decision-makers: Technological Status and Potential Role in Energy Economy*

Springer.

Perry, A. M., Marland, G., & Zelby, L. W. (1977). *Net energy analysis of an ocean thermal energy conversion (OTEC) system* (No. ORAU/IEA(M)-77-1 United StatesTue Feb 12

19:16:05 EST 2008Dep. NTIS, PC A04/MF A01.ERA-02-051233; EPA-; EDB-77-124826English).

Peter, S., & Lehmann, H. (2007). *Renewable Energy Outlook 2030: Energy Watch Group Global Renewable Energy Scenarios*: Energy Watch Group.

Phylipsen, G. J. M., & Alsema, E. A. (1995). *Environmental life-cycle assessment of multicrystalline silicon solar cell modules* (No. Report no. 95057): Netherlands Agency for Energy and the Environment, NOVEM.

Piccolo, C., & Bezzo, F. (2009). A techno-economic comparison between two technologies for bioethanol production from lignocellulose. *Biomass and Bioenergy, 33*(3), 478-491.

Pierce, B. S. (2007). *Geologic Endowment*: National Petroleum Council.

Pimentel, D., & Patzek, T. W. (2005). Ethanol Production Using Corn, Switchgrass, and Wood; Biodiesel Production Using Soybean and Sunflower. *Natural Resources Research, 14*(1), 65-76.

Podolinsky, S. (1883). Menschliche Arbeit und Einheit der Kraft. *Die Neue Zeit, Vol. 1,*.

Porter, P. A., Barry, J., Samson, R., & Doudlah, M. (2008). *Growing Wisconsin Energy: A Native Grass Pellet Bio-Heat Roadmap for Wisconsin*: Agriculture Diversification and Development Program, Wisconsin Department of Agriculture Trade and Consumer Protection, .

Pradhan, A., Shrestha, D. S., Van Gerpen, J., & Duffield, J. (2008). The Energy Balance of Soybean Oil Biodiesel Production: A Review of Past Studies. *Transactions of the ASABE, 51*(1), 185-194.

Prakash, R., Henham, A., & Bhat, I. K. (1998). Net energy and gross pollution from bioethanol production in India. *Fuel, 77*(14), 1629-1633.

Prasad, A. R. (1986). *Coal Industry of India*: APH Publishing.

Pro, B. H., Hammerschlag, R., & Mazza, P. (2005). Energy and land use impacts of sustainable transportation scenarios. *Journal of Cleaner Production, 13*(13-14), 1309-1319.

Prueksakorn, K., & Gheewala, S. H. (2008). Full Chain Energy Analysis of Biodiesel from Jatropha curcas L. in Thailand. *Environmental Science & Technology, 42*(9), 3388-3393.

Qadeer, A. (1981). A Multilateral Agreement on Oil. *Houston Journal of International Law, 3*(1).

Quesnay, F., Kuczynski, M., & Meek, R. L. (1972). *Quesnay's 'Tableau économique'*. London: Macmillan for the Royal Economic Society and the American Economic Association.

Rao, S., Riahi, K., Stehfest, E., van Vuuren, D., Cho, C., den Elzen, M., et al. (2008). *IMAGE and MESSAGE Scenarios Limiting GHG Concentration to Low Levels* IIASA.

Rauh, A. & Seelert,W. (1984) The Betz optimum efficiency for windmills. *Applied Energy, 17*(1), 15–23.

Rees, J. (1985). *Natural resources : allocation, economics and policy*. London u.a: Methuen.

Regemorter, D. v., & Goldstein, D. (1998). *Development of MARKAL - Towards a Partial Equilibrium Model*: Energy Technology Systems Analysis Program.

Rempel, H., Schmidt, S., & Schwarz-Schampera, U. (2006). *Reserves, Resources and Availability of Energy Resources 2006*.

Reynolds, D. (1998). Entropy subsidies. *Energy Policy, 26*(2), 113-118.

Reynolds, D. B. (1999). The mineral economy: how prices and costs can falsely signal decreasing scarcity. *Ecological Economics, 31*(1), 155-166.

Reynolds, D. B. (2000). The case for conserving oil resources: the fundamentals of supply and demand. *OPEC Review*.

Rhyd, C. J., & Sandén, B. A. (2005). Energy analysis of batteries in photovoltaic systems. Part II: Energy return factors and overall battery efficiencies. *Energy Conversion and Management, 46*, 1980-2000.

Ricardo, D. (1923). *Economic essays edited with introductory essay and notes*. London: G. Bell and Sons.

Richards, B. S., & Watt, M. E. (2007). Permanently dispelling a myth of photovoltaics via the adoption of a new net energy indicator. *Renewable & Sustainable Energy Reviews, 11*(1), 162-172.

Rizwan, M., Jamil, M., & Kothari, D. P. Solar energy estimation using REST model for PV-ECS based distributed power generating system. *Solar Energy Materials and Solar Cells, In Press, Corrected Proof.*

Robelius, F. (2007). *Giant Oil Fields - The Highway to Oil. Giant Oil Fields and their Importance for Future Oil Production.* Uppsala University.

Rombough, C. T., & Koen, B. V. (1975). Total energy investment in nuclear power plants. *Nuclear Technology, 26*, 5-11.

Roques, F., Nuttall, W. J., Newbery, D. M., & De Neufville, R. (2006). Nuclear power: a hedge against uncertain gas and carbon prices?

Rotty, R. M., Perry, A. M., & Reister, D. B. (1975). *Net energy from nuclear power*: Institute for Energy Analysis, Oak Ridge Associated Universities.

Ruark, G., Josiah, S., Riemenschneider, D., & Volk, T. (2006). *Perennial Crops for Bio-fuels and Conservation*. Paper presented at the USDA Agricultural Outlook Forum – Prospering In Rural America from http://www.usda.gov/oce/forum/2006%20Speeches/PDF%20speech%20docs/Ruark2806.pdf

Ryan, G. J. (1995). *Dynamic Physical Analysis of Long-term Economy-Environment Options.* University of Canterbury, Christchurch, New Zealand.

Salameh, M. G. (2000). Global oil outlook: return to the absence of surplus and its implications. *Applied energy*, *65*(1-4), 239-250.

Samuelson, P. A. (Ed.). (1969). *Classical and neoclassical theory*.

Sauter, V. (2008). Systems Theory: Classnotes for Information Systems Analysis at University of Missouri - St. Louis Retrieved 8th February, 2010, from http://www.umsl.edu/~sauterv/analysis/intro/system.htm

Schenk, N. J., & Moll, H. C. (2007). The use of physical indicators for industrial energy demand scenarios. *Ecological Economics, 63*(2-3), 521-535.

Schipper, L., Unander, F., Murtishaw, S., & Ting, M. (2001). INDICATORS OF ENERGY USE AND CARBON EMISSIONS: Explaining the Energy Economy Link. *Annual Review of Energy and the Environment, 26*(1), 49-81.

Schock, R. N. (2005). Energy Technologies for the 21st Century-The Roles of Renewable Energy. In R. C. Ragaini (Ed.), *International Seminar on Nuclear War and Planetary Emergencies : 32nd session : the 32nd session of and international collaboration : "E. Majorana" Centre for Scientific Culture, Erice, Italy, 19-24 Aug 2004* (pp. xiii, 520 p.). New Jersey ; London: World Scientific.

Schrödinger, E. (1944). *What is Life?* : Cambridge University Press.

Schumpeter, J. A. (1994). *Capitalism, socialism, and democracy* (5th ed.). London: Routledge.

SDC (2009). Sustainable Development Commission - A Brief History of Sustainable Development Retrieved 30/12/2009, 2009, from http://www.sd-commission.org.uk/pages/a-brief-history-of-sustainable-development.html&

Seebregts, A. J., Goldstein, G. A., & Smekens, K. (2001). *Energy/Environmental Modeling with the MARKAL Family of Models*. Paper presented at the International Conference on Operations Research.

Shapouri, H., Duffield, J., & McAloon, A. (2004). *The 2001 Net Energy Balance of Corn-Ethanol*: Agricultural Research Service, USDA.

Shapouri, H., Duffield, J. A., & Graboski, M. S. (1995). *Estimating the Net Energy Balance of Corn Ethanol*: Economic Research Service, Office of Energy, U.S. Department of Agriculture.

Shapouri, H., Wang, M., & Duffield, J. (2006). Net Energy Balancing and Fuel-Cycle Analysis. In J. Dewulf & H. Van Langenhove (Eds.), *Renewables-Based Technology: Sustainability Assessment*: John Wiley & Sons.

Sheehan, J., Camobreco, V., Duffield, J., Graboski, M., & Shapouri, H. (1998). *Life cycle inventory of biodiesel and petroleum diesel for use in an urban bus. Final report* (No. NREL/SR--580-24089; Other: ON: DE98005500; TRN: US200311%%454 United States10.2172/658310Other: ON: DE98005500; TRN: US200311%%454Tue Feb 05 03:01:36 EST 2008OSTI as DE98005500NREL; RN03049929English).

Shell (1995). *The evolution of the world's energy system 1860-2060*. London, U.K.: Shell International

Sidney, K., Hemingway, E. L., & Berkshire, L. H. (1976). *Basic estimated capital investment and operating costs for coal strip mines* (No. Information circular FY 76). Morgantown, WV (USA): Bureau of Mines, Process Evaluation Group.

Sims, R. E. H. (2008). Hydropower, Geothermal and Ocean Energy. *MRS Bulletin*, *33*, 389-395.

Slesser, M. (1992). ECCO: User's Manual. In Resource Use Institute (Ed.). Edinburgh, Scotland.

Slesser, M., King, J., & Crane, D. C. (1997). *The management of greed : a bio-physical appraisal of economic and environmental potential*. Edinburgh: RUI Publishing.

Smil, V. (2003). *Energy at the crossroads : global perspectives and uncertainties*. Cambridge, Mass.: MIT Press.

Smil, V. (2006). *Energy at the Crossroads*. Paper presented at the Scientific Challenges for Energy Research.

Smil, V. (2008). *Energy in nature and society : general energetics of complex systems*. Cambridge, Mass.: The MIT Press.

Smith, V. K. (1980). The Evaluation of Natural-Resource Adequacy - Elusive Quest or Frontier of Economic-Analysis. *Land Economics*, *56*(3), 257-298.

Soddy, F. (1922). *Cartesian economics; the bearing of physical science upon state stewardship*. London,: Hendersons.

Soddy, F. (1926). *Wealth, virtual wealth and debt : the solution of the economic paradox*. [S.l.]: Allen & U.

Solow, R. M. (1957). Technical Change and the Aggregate Production Function. *The Review of Economics and Statistics, 39*(3), 312-320.

Solow, R. M. (1974). Intergenerational Equity and Exhaustible Resources. *The Review of Economic Studies, 41*, 29-45.

Spath, P. L., Mann, M. K., & Kerr, D. R. (1999). *Life Cycle Assessment of Coal-Fired Power Production*. from http://www.osti.gov/bridge.

Starr, C., Milton, F. S., & Alpert, S. (1992). Energy Sources: A Realistic Outlook. *Science, 256*(5059), 981-987.

Steele, H. (1979). *The economic potentialities of synthetic liquid fuels from oil shale*. New York: Arno Press.

Streicher, E., Heidemann, W., & Müller-Steinhagen, H. (2004, 20 - 23 June 2004). *Energy Payback Time – A Key Number for the Assessment of Thermal Solar Systems.* Paper presented at the EuroSun2004, Freiburg, Germany.

Szasz, D. (2000). Boltzmann's ergodic hypothesis, a conjecture for centuries? *Hard ball systems and the Lorentz gas*, 421.

Tainter, J. A. (1988). *The collapse of complex societies*. Cambridge, Cambridgeshire ; New York: Cambridge University Press.

Taylor, P. G., d'Ortigue, O. L., Francoeur, M., & Trudeau, N. Final energy use in IEA countries: The role of energy efficiency. *Energy Policy, In Press, Corrected Proof*.

Tedeschi, R. G., & Calhoun, L. G. (1995). *Trauma and transformation: Growing in the aftermath of suffering*. Thousand Oaks, CA: Sage.

Théry, I., Gril, J., Vernet, J. L., Meignen, L., & Maury, J. (1996). Coal used for Fuel at Two Prehistoric Sites in Southern France: Les Canalettes (Mousterian) and Les Usclades (Mesolithic). *Journal of Archaeological Science, 23*(4), 509-512.

Thomas, D. I. (1974). *Resources and Energy: A Global Study of the Factors Influencing their Acquisition*: Merlwood Research Station.

Tonelli, I. F. (2007). Using System Dynamic in Operations Management. Universita degli Studi di Genova.

Tovey, T. (2008). Performance of two photovoltaic arrays in the UK *Energy, 161*(1), 11-21.

Trainer, F. E. (2007). *Renewable energy cannot sustain a consumer society*. Dordrecht, The Netherlands: Springer.

Tsao, J., Lewis, N., & Crabtree, G. (2006). *Solar FAQ's*: US Department of Energy.

Tunji, A. (1986). World Primary Energy Consumption - a look through growth curves with upper limits. *OPEC Review, 10*(1), 103-118.

Turton, H., & Barreto, L. (2004). *The extended energy-systems ERIS model: An overview* IIASA.

Turton, H., & Barreto, L. (2006). Long-term security of energy supply and climate change. *Energy Policy, 34*(15), 2232-2250.

UCS (1992). *World Scientists' Warning to Humanity*

UK Govt. (2005). *The UK Government Sustainable Development Strategy: Securing the Future*.

Ulph, A. M. (1980). World energy models--a survey and critique. *Energy Economics, 2*(1), 46-59.

UN (1987). *Report of the World Commission on Environment and Development: Our Common Future* (No. Annex to A/42/427): United Nations.

UN (1997). Earth Summit: UN Conference on Environment and Development (1992) Retrieved 30/12/2009, 2009, from http://www.un.org/geninfo/bp/enviro.html

UN (2002). *Report of the World Summit on Sustainable Development* (No. ISBN 92-1-104521-5). Johannesburg, South Africa, : United Nations.

UN (2009). UN Energy Statistics Database. Retrieved 15/03/2009, from United Nations Statistics Division: http://data.un.org/Browse.aspx?d=EDATA

UNDP (2000). *Human development report*: United Nations Development Programme.

USGS (2000). *World Petroleum Assessment*: United States Geological Survey.

Uzunoz, M., Akcay, Y., & Esengun, K. (2008). Energy Input-output Analysis of Sunflower Seed (*Helianthus annuus* L.) Oil in Turkey. *Energy Sources, Part B: Economics, Planning, and Policy, 3*(3), 215 - 223.

Vadas, P., Barnett, K., & Undersander, D. (2008). Economics and Energy of Ethanol Production from Alfalfa, Corn, and Switchgrass in the Upper Midwest, USA. *BioEnergy Research, 1*(1), 44-55.

van Ruijven, B., Urban, F., Benders, R. M. J., Moll, H. C., van der Sluijs, J. P., de Vries, B., et al. (2008). Modeling Energy and Development: An Evaluation of Models and Concepts. *World Development, 36*(12), 2801-2821.

van Sark, W. G. J. H. M., Patel, M. K., Faaij, A., & Hoogwijk, M. (2006). The Potential of Renewables as Feedstocks for Chemistry and Energy. In J. Dewulf & H. Van Langenhove (Eds.), *Renewables-Based Technology: Sustainability Assessment*: John Wiley & Sons.

Vattenfall (1999). *Vattenfall's Life Cycle Studies of Electricity* Stockholm, Sweden: Vattenfall.

Ventana (1988-2008). VenSim Professional for Windows (Version 5.9c).

Venturi, P., & Venturi, G. (2003). Analysis of energy comparison for crops in European agricultural systems. *Biomass and Bioenergy, 25*(3), 235-255.

Volk, T. A., Tharakan, P. J., Abrahamson, L. P., White, E. H., & Pimentel, D. (2003). Greater Potential for Renewable Biomass Energy. *BioScience, 53*(7), 620-621.

von Blottnitz, H., & Curran, M. A. (2007). A review of assessments conducted on bio-ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective. *Journal of Cleaner Production, 15*, 607-619.

Voss, A. (2001). *LCA and External Costs in Comparitive Assessment of Electricity Chains. Decision Support for Sustainable Electricity Provision*. Paper presented at the Externalities and Energy Policy: The Life Cycle Analysis Approach.

Wagner, H. J., & Pick, E. (2004). Energy yield ratio and cumulative energy demand for wind energy converters. *Energy, 29*(12-15), 2289-2295.

Watt, M. (Producer). (2006) Photovoltaics in Australia: Technology, Markets & Performance.

WEA (2000). *World Energy Assessment: Energy and the Challenge of Sustainability*. New York: UNDP.

WEC (1974 -). *World Energy Conference survey of energy resources*: London : WEC Central Office, 1974-.

WEC (2003). *Renewable Energy Targets*. London: World Energy Council.

WEC (2007). *Survey of Energy Resources*: World Energy Council.

White, L. A. (1943). Energy and the Evolution of Culture. *American Anthropologist, 45*(3), 335-356.

White, S. W. (1998). *Net Energy Payback andCO2 Emissions from Helium-3 Fusion and Wind Electrical Power Plants* (No. UWFDM-1093). Madison, WI, USA: University of Wisconsin.

White, S. W., & Kulcinski, G. L. (1998). *Net Energy Payback and CO2 Emissions from Wind-Generated Electricity in the Midwest* (No. UWFDM-1092). Madison, WI, USA. : University of Wisconsin.

White, S. W., & Kulcinski, G. L. (1999). Birth to death analysis of the energy payback ratio and CO2 gas emission rates from coal, fission, wind, and DT-fusion electrical power plants. *Fusion Engineering and Design, 48*(248), 473-481.

White, S. W., & Kulcinski, G. L. (2000). Birth to death analysis of the energy payback ratio and CO2 gas emission rates from coal, fission, wind, and DT-fusion electrical power plants. *Fusion Engineering and Design, 48*(3-4), 473-481.

Wiener, N. (1948). *Cybernetics, or, Control and communication in the animal and the machine*. New York: Wiley.

Williams, R. H. (1995). *Variants of a low CO2 -emitting energy supply system (LESS) for the world*. Richland: Pacific Northwest Laboratories.

Wilson, D., & Swisher, J. (1993). Exploring the gap : Top-down versus bottom-up analyses of the cost of mitigating global warming. *Energy Policy, 21*(3), 249-263.

Wilson, R., & Young, A. (1996). The embodied energy payback period of photovoltaic installations applied to buildings in the UK. *Building and Environment, 31*(4), 299-305.

WindPower (1997). *The Energy Balance of Modern Wind Turbines*.

Wood, J. H., Long, G. R., & Morehouse, D. F. (2002). *Long-Term World Oil Supply Scenarios*: Energy Information Administration, US Department of Energy.

Wood, J. H., Long, G. R., & Morehouse, D. F. (2004, Page last modified on Thu Aug 19 2004 05:08:19 GMT+1200 (New Zealand Standard Time)). Long-Term World Oil Supply Scenarios: The Future is Neither as Bleak or as Rosy as Some Assert Retrieved 11th Dec 2009, from http://www.eia.doe.gov/pub/oil_gas/petroleum/feature_articles/2004/worldoilsupply/oilsupply04.html

Worrell, E., Price, L., Martin, N., Farla, J., & Schaeffer, R. (1997). Energy intensity in the iron and steel industry: a comparison of physical and economic indicators. *Energy Policy, 25*(7-9), 727-744.

WWEC (2008). *World Wind Energy Report 2008*: World Wind Energy Council.

Yuan, J. S., Tiller, K. H., Al-Ahmad, H., Stewart, N. R., & Stewart Jr, C. N. (2008). Plants to power: bioenergy to fuel the future. *Trends in Plant Science, 13*(8), 421-429.

Zerta, M., Schmidt, P. R., Stiller, C., & Landinger, H. (2008). Alternative World Energy Outlook (AWEO) and the role of hydrogen in a changing energy landscape. *International Journal of Hydrogen Energy, 33*(12), 3021-3025.

Zhang, Z., & Folmer, H. (1998). Economic modelling approaches to cost estimates for the control of carbon dioxide emissions. *Energy Economics, 20*(1), 101-120.

Zittel, W., & Schindler, J. (2006). *Uranium Resources and Nuclear Energy*: Energy Watch Group.

Zucchetto, J. (2004). Reflections on Howard T. Odum's paper: *Energy,Ecology and Economics*, Ambio, 1973. *Ecological Modelling, 178*, 195-198.

Zucchetto, J., & Brown, S. (1977). Comparison of Fossil-Fuel Energy-Requirements for Solar, Natural-Gas, and Electrical Water Heating Systems. *Resource Recovery and Conservation, 2*(4), 283-300.

APPENDICES

APPENDIX A. ESTIMATES OF HISTORIC ENERGY PRODUCTION

A.1 Coal

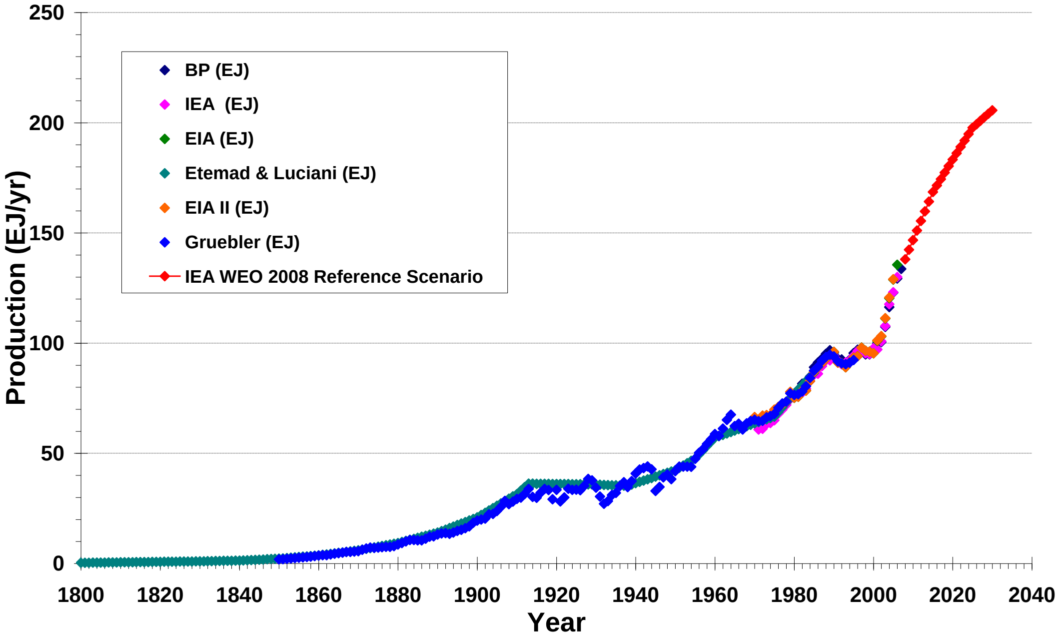


Figure A-1 Annual coal production from various sources (BP, 2008; EIA, 2006, 2007; Etemad & Luciani, 1991; IEA, 2008a, 2008c)

A.2 Conventional oil

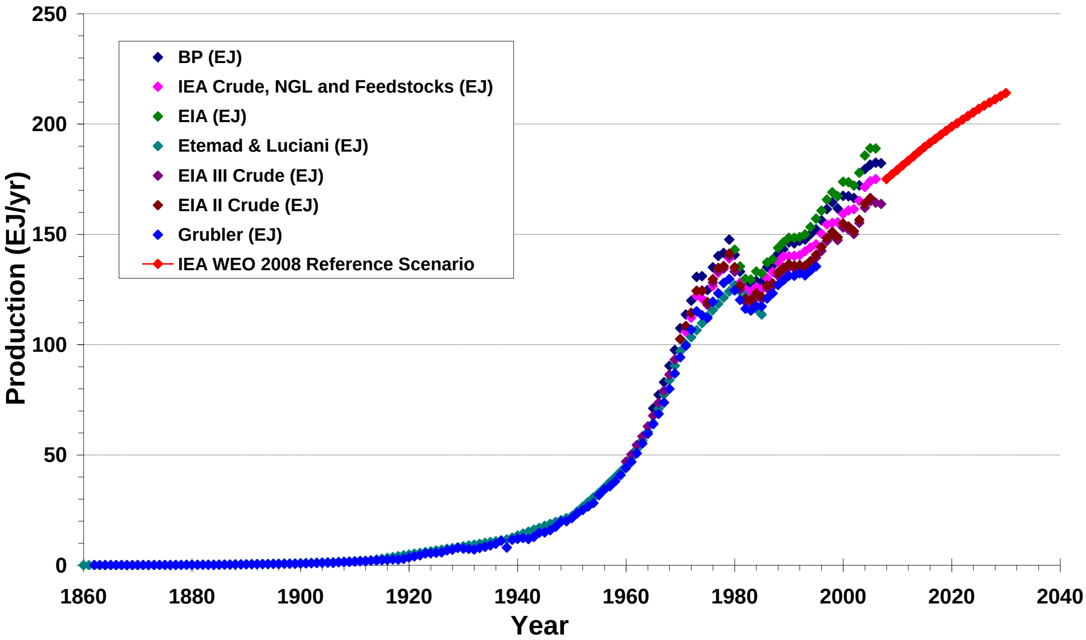


Figure A-2 Annual conventional oil production from various sources, (BP, 2008; EIA, 2006, 2007, 2008; Etemad & Luciani, 1991; IEA, 2008a)

A.3 Unconventional oil

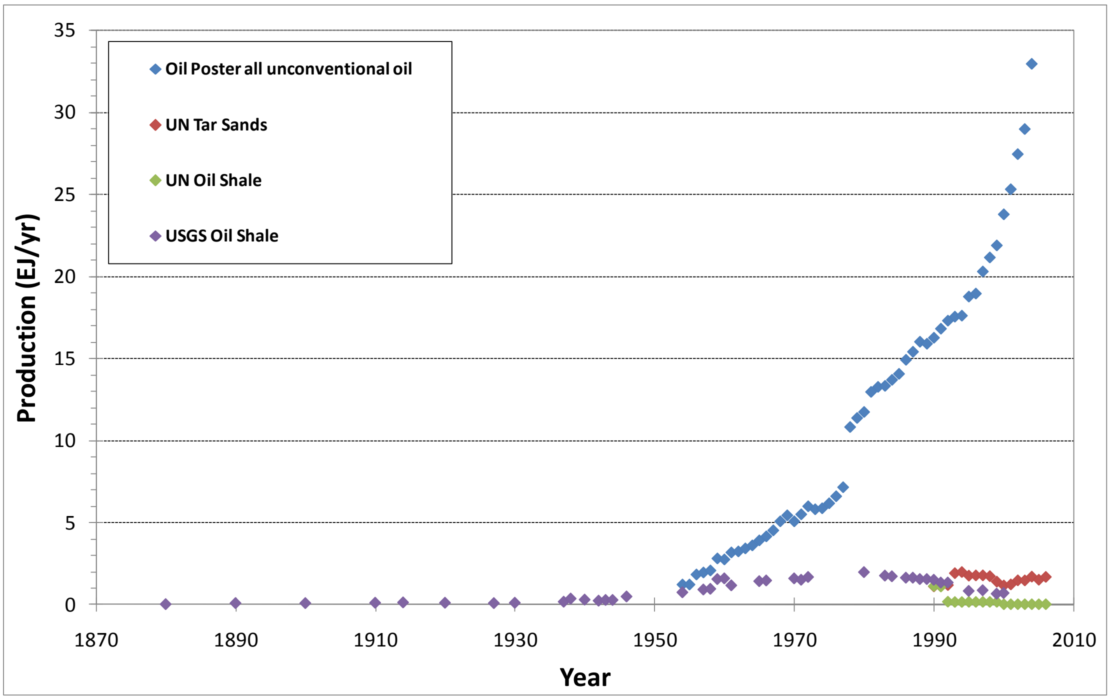


Figure A-3 Annual unconventional oil production from various sources, (Bracken & Menninger, 2005; UN, 2009; USGS, 2000)

A.4 Conventional gas

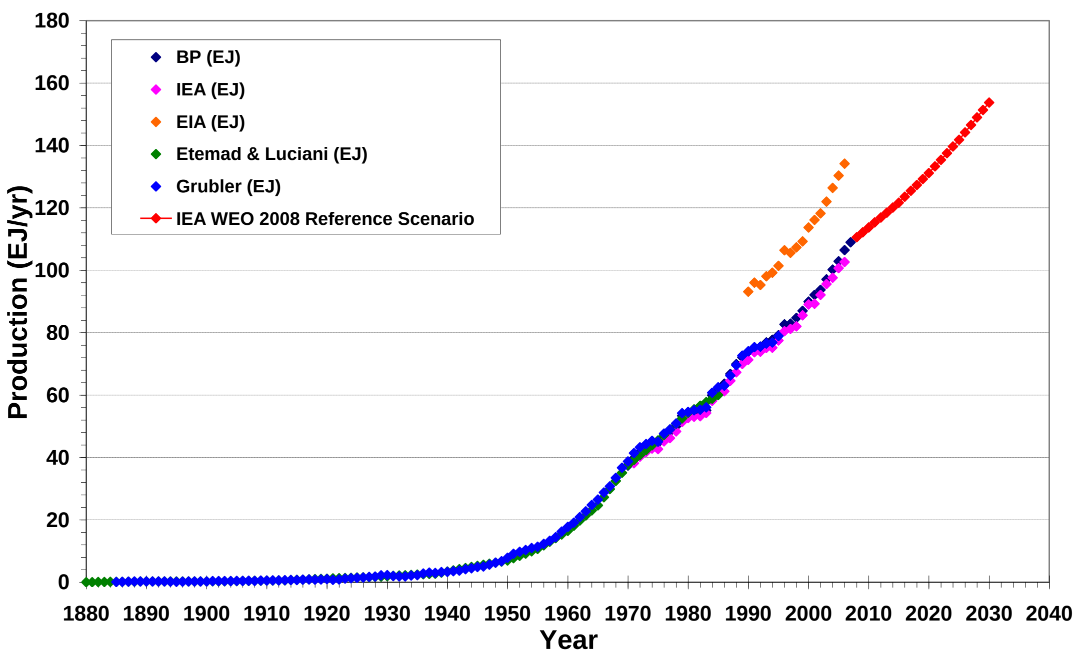


Figure A-4 Annual natural gas production from various sources, (BP, 2008; EIA, 2006, 2007; Etemad & Luciani, 1991; IEA, 2008a)

A.5 Nuclear Fission

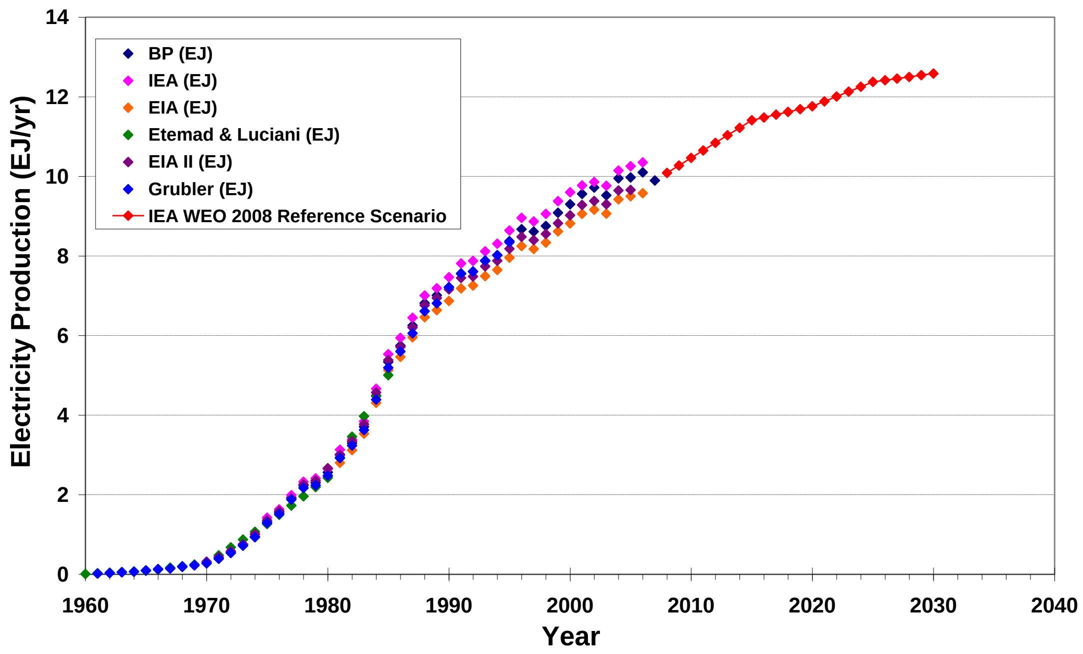


Figure A-5 Annual nuclear energy generation from various sources, (BP, 2008; EIA, 2006, 2007; Etemad & Luciani, 1991; IEA, 2008a)[43]

A.6 Biomass

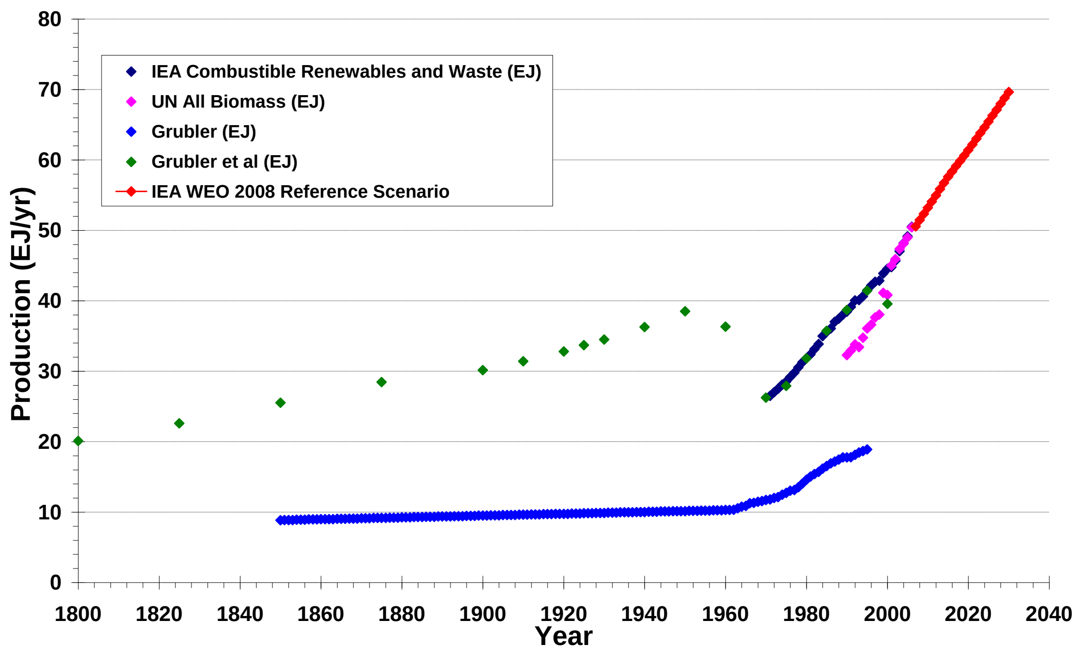


Figure A-6 Annual biomass production from various sources, (Grübler, 1998; Grübler, et al., 1996; IEA, 2008a, 2008c; UN, 2009)

[43] The figures for nuclear (electricity) production presented here are less than the EIA 2006 and IEA 2008 values by a factor of three. This discrepancy was presumably to account for primary thermal energy normally expended in producing electricity, as most thermal power plants are around 33% efficient.

A.7 Hydro

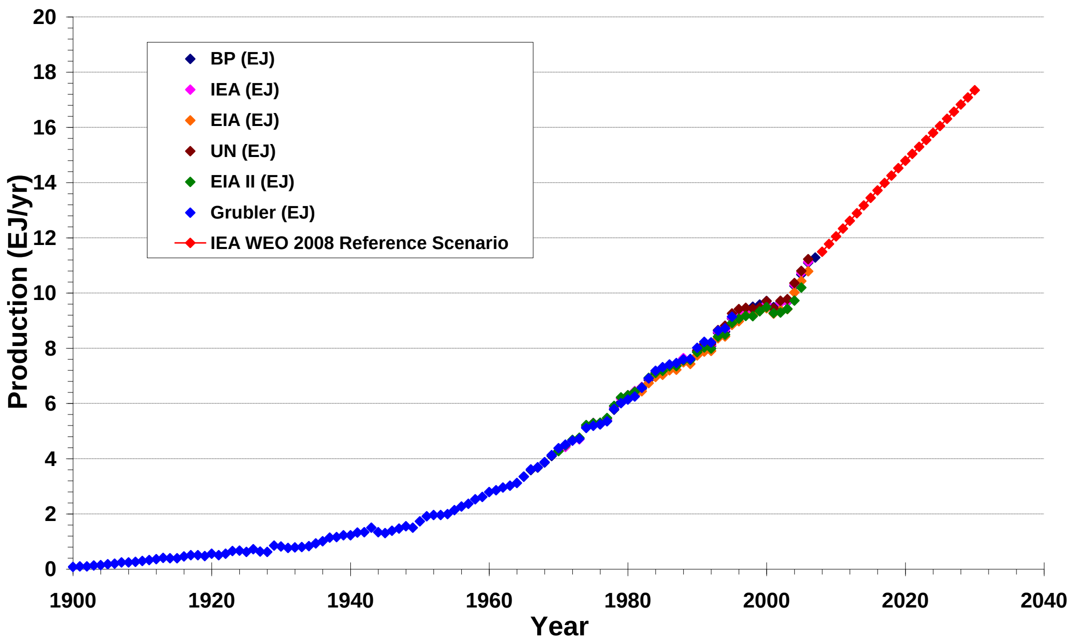


Figure A-7 Annual hydro-electric production from various sources, (BP, 2008; EIA, 2006, 2007; IEA, 2008a; UN, 2009)

A.8 Geothermal

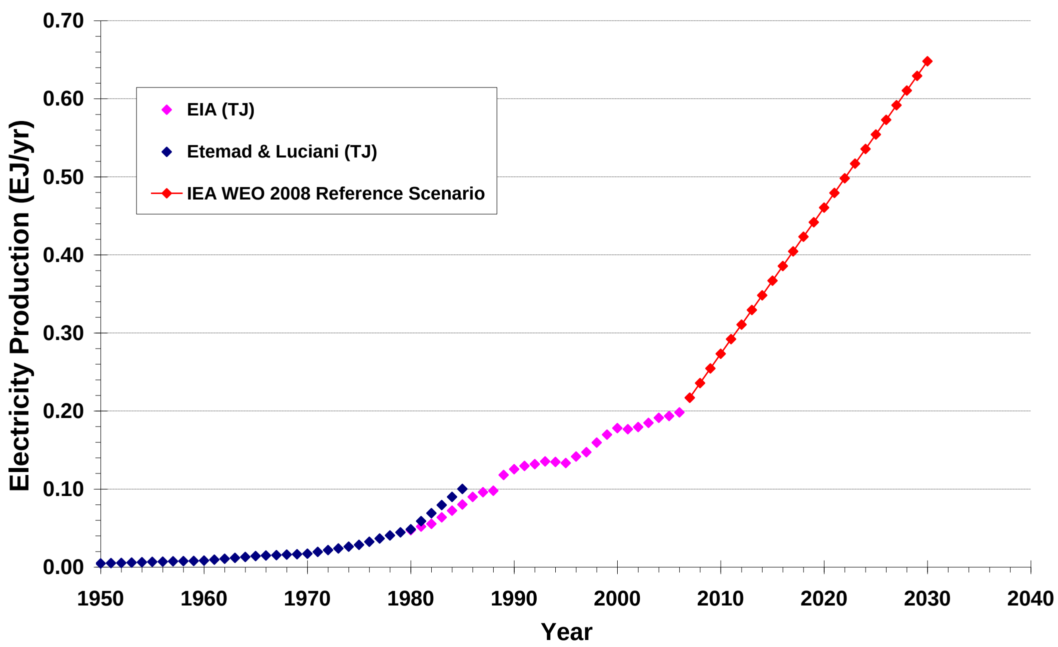


Figure A-8 Annual production of electricity from geothermal sources, with data from (EIA, 2007; Etemad & Luciani, 1991; IEA, 2008c)

A.9 Tidal

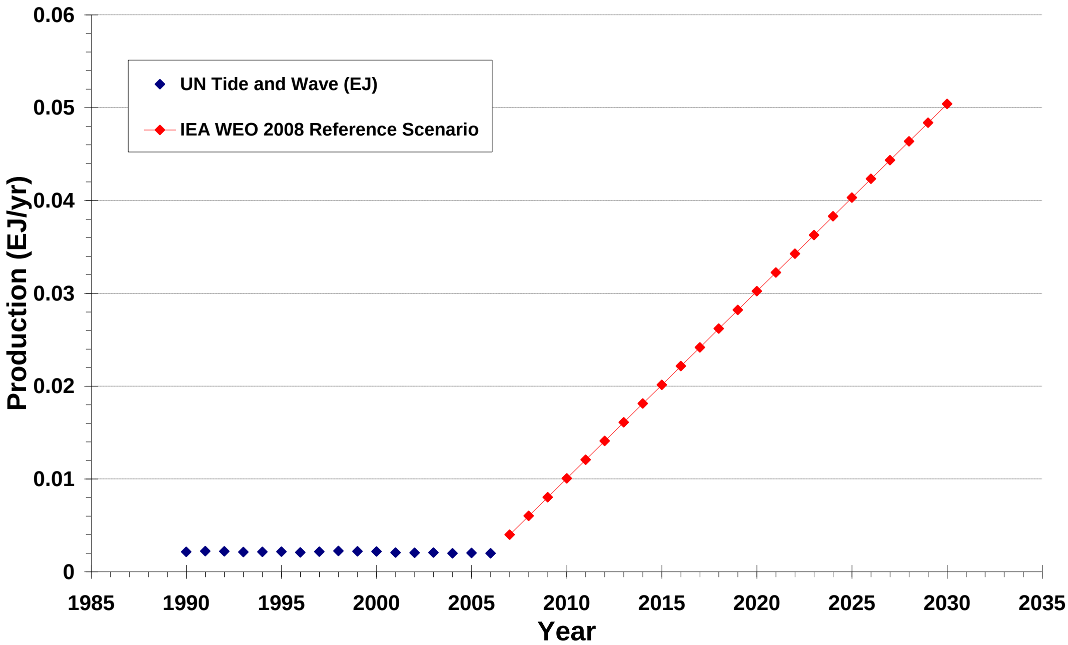


Figure A-9 Annual tidal production, (UN, 2009)

A.10 Wind

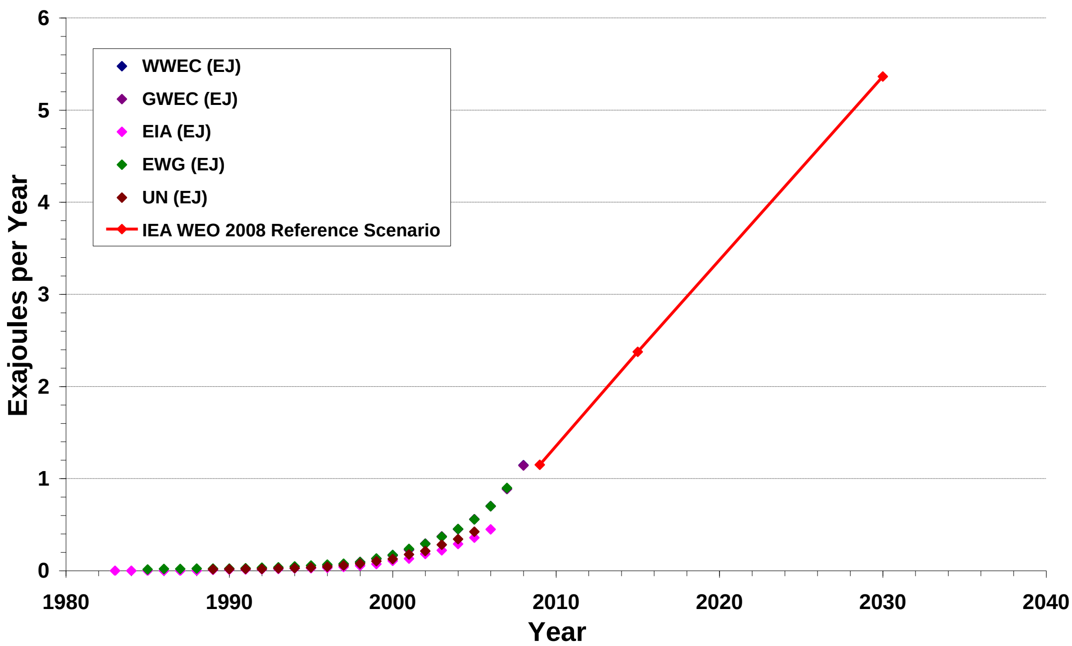


Figure A-10 Annual wind energy production from various sources, (EIA, 2006; EWG, 2009; GWEC, 2009; IEA, 2008c; UN, 2009; WWEC, 2008)

A.11 Solar

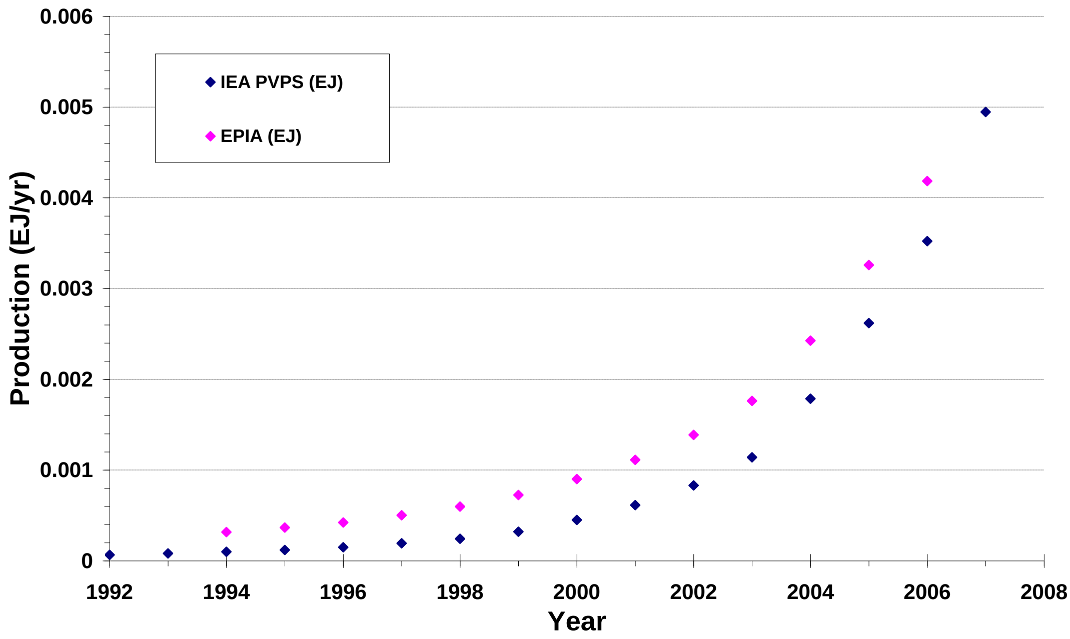


Figure A-11 Annual PV production from various sources, (EPIA, 2007; IEA, 2008b)

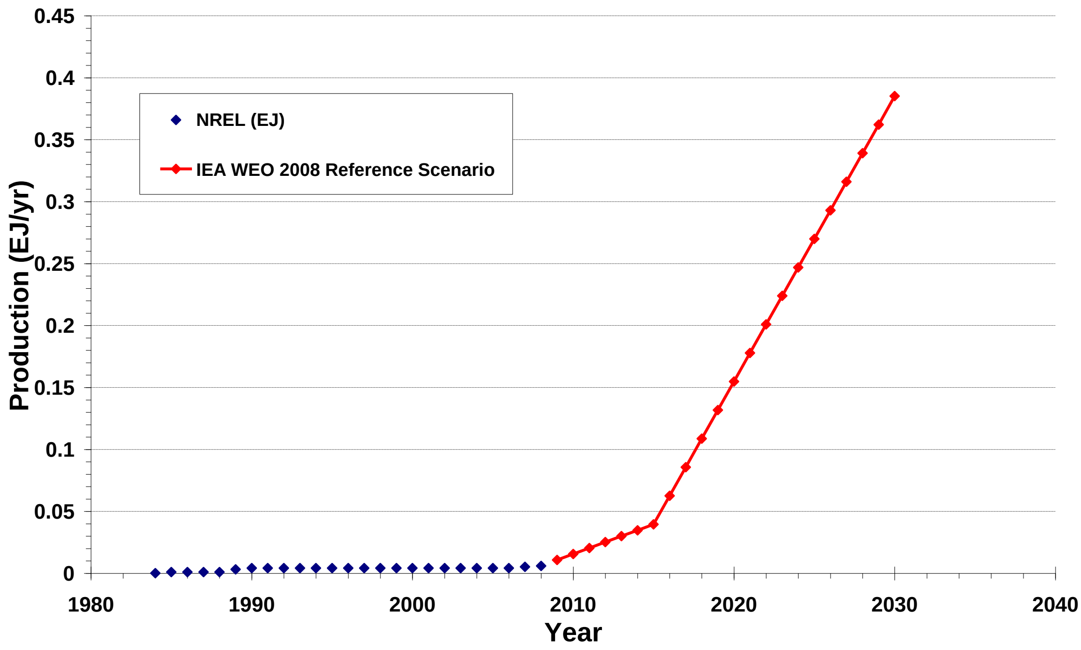


Figure A-12 Annual production of electricity from concentrating solar power (CSP), with data from (IEA, 2008c; NREL, 2009)

APPENDIX B. ESTIMATES OF EROI OF ENERGY SOURCES

B.1 Coal

Table B-1 Estimates of EROI for coal production

YEAR	PRIMARY SOURCE						SECONDARY SOURCE					
	PEER REVIEWED			NON-PEER REVIEWED			PEER REVIEWED			NON-PEER REVIEWED		
	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR
1929				Hall et al. (1986)	28							
1933				Leach (1976)	22							
1939				Hall et al. (1986)	29							
1950	Cleveland (2005)	100										
1954				Hall et al. (1986)	29							
1955	Cleveland et al. (1984)	73		Hall et al. (1986)	80							
1958	Cleveland et al. (1984)	70		Hall et al. (1986)	30							
1963	Cleveland et al. (1984)	72										
1963	Chapman et al. (1974)	22.17										
1964				Hall et al. (1986)	34							
1965	Cleveland et al. (1984)	80										
1967	Cleveland et al. (1984)	80		Hall et al. (1986)	36							
1968				Leach (1976)	25							

1968	Chapman et al. (1974)	24.94						
1971			Leach (1976)	22			Chapman (1974) from Boustead & Hancock	7.33
1972	Cleveland et al. (1984)	52	Hall et al. (1986)	26				
1972	Chapman et al. (1974)	22						
1974	Chapman et al. (1974)	6						
1975			Hall et al. (1986)	30				
1976			Duda & Hemingway (1976)	333				
1976			Sidney et al. (1976)					
1977	Cleveland et al. (1984)	31	Hall et al. (1986)	20				
1977	Cleveland et al. (1984)	30	Leach (1977)	49				
1977			Leach (1977)	44				
1977			Leach (1977)	19				
1977			Leach (1977)	17				
1977			Leach (1977)	11				
1977			Leach (1977)	12				
1977			Leach (1977)	44				
1977			Leach (1977)	39				
1979			Boustead & Hancock (1979)	400				
1979			Boustead & Hancock (1979)	2.56				
1996			Odum (1996)	12.5				
1996			Odum (1996)	10.5				
1996			Odum (1996)	6.8				

1996			Odum (1996)	2.2						
2000	Cleveland (2005)	80								
2003								Smil (2003)	10	
2003								Smil (2003)	53.3	47
2006	Shapouri et al. (2006)	50								
2007								Fleay (2007)	26.3	
2007								Fleay (2007)	45	
2007								Fleay (2007)	12.7	
2007								Fleay (2007)	50	
2007					Li (2007) [Electricity]	5.75		Fleay (2007)	9.3	
2007								Fleay (2007)	13.5	
2007								Fleay (2007)	15	
2008					Kubiszweski & Cleveland (2008)	8	3	Smil (2008)	5.8	
2008								Smil (2008)	3.75	
2008								Smil (2008)	125	
2008								Hopkins (2008)	62	
2008								Hopkins (2008)	3	

Table B-2 Estimates of EROI for coke production

YEAR	PRIMARY SOURCE						SECONDARY SOURCE					
	PEER REVIEWED			NON-PEER REVIEWED			PEER REVIEWED			NON-PEER REVIEWED		
	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR
1963										Chapman (1974) [Coke] from Bousted & Hancock (1979)	3.09	
1966										Leach (1976) [Coke] from Boustead & Hancock (1979)	5.54	
1968										Chapman (1974) [Coke] from Bousted & Hancock (1979)	5.54	
1968										Chapman (1974) [Coke] from Bousted & Hancock (1979)	2.56	
1974										Samples (1974) [Coke] from Boustead & Hancock	6.4	
1975										Barnes (1975) [Coke] from Boustead & Hancock (1979)	3.55	
1975										Leach (1976) [Coke] from Boustead & Hancock (1979)	3.22	

1976			Chapman (1974) [Coke] from Boustead & Hancock (1979)	
1976			Waller (1976) [Coke] from Boustead & Hancock (1979)	2.75
1976			Gartner (1976) [Coke] from Boustead & Hancock (1979)	
1979	Boustead & Hancock (1979) [Coke]	4.29		

Table B-3 Estimates of EROI for production of other fuels (CtX) from coal

YEAR	PRIMARY SOURCE						SECONDARY SOURCE					
	PEER REVIEWED			NON-PEER REVIEWED			PEER REVIEWED			NON-PEER REVIEWED		
	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR
1963										Chapman (1974) [Coal gas] from Boustead & Hancock (1979)	1.84	
1971										Chapman (1974) [Coal gas] from Boustead & Hancock (1979)	4.29	
1973										Leach (1976) [Coal gas] from Boustead & Hancock	3.26	
1974				Oil & Gas Journal (1974)	2.6	0.4						
1977	Leach (1977) [Coal to high Bth gas]	46.5	2.5									
1977	Leach (1977) [Coal to low Bth gas]	18	1									
1977	Leach (1977) [Coal to oil]	11.5	0.5									
1977	Leach (1977) [Coal to methanol]	41.5	2.5									
2005	Cleveland (2005) [CtL]	5	5									

Table B-4 Estimates of EROI for production of electricity from coal

YEAR	PRIMARY SOURCE						SECONDARY SOURCE					
	PEER REVIEWED			NON-PEER REVIEWED			PEER REVIEWED			NON-PEER REVIEWED		
	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR
1974	Gilliland (1975) [Electricity]	4										
1986				Hall et al. (1986) [Electricity]	4.35							
1986				Hall et al. (1986) [Electricity]	9							
1986				Hall et al. (1986) [Electricity]	6							
1986				Hall et al. (1986) [Electricity]	2.5							
1997	Akai et al. (1997) [Electricity – IGCC]	10										
1997	Akai et al. (1997) [Electricity – IGCC with CCS]	6.71										
1998							Prakash et al. (1998) [Electricity]	8.6				
1999	White & Kulcinski (1999) [Electricity]	11		Spath et al. (1999) [Electricity]	3	2						

1999		Spath et al. (1999) [Electricity]	6.5	0.5		
1999		Spath et al. (1999) [Electricity]	6.7			
2000		IEA BioEnergy (2000) [Electricity]	4.97			
2000		IEA BioEnergy (2000) [Electricity – NSPS Plant]	5.09			
2000		IEA BioEnergy (2000) [Electricity – LEBS Plant]	6.72		Gagnon (2008) [Electricity]	3.8
2001		Voss (2001) [Electricity]	66.67			
2001		Voss (2001) [Electricity from Lignite]	88.89			
2002		Meier & Kulcinski [Electricity]	11			
2002					Gagnon (2002) [Electricity]	6
2003					Gagnon (2008) [Electricity with CCS]	
2008					Lund & Biswas (2008) [Electricity]	3.8
2008					Lund & Biswas (2008) [Electricity – IGCC]	5.25

2008	Lund & Biswas (2008) [Electricity with CCS]	2.45

B.2 Conventional oil

Table B-5 Estimates of EROI for conventional oil production [World]

YEAR	**PRIMARY SOURCE**						**SECONDARY SOURCE**					
	PEER REVIEWED			NON-PEER REVIEWED			PEER REVIEWED			NON-PEER REVIEWED		
	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR
1919				Hall (2010) [World – pc]	20	0						
1963	Cleveland et al. (1984) [World]	17										
1964	Cleveland et al. (1984) [World]	18										
1965	Cleveland et al. (1984) [World]	19										
1966	Cleveland et al. (1984) [World]	20										
1967	Cleveland et al. (1984) [World]	21										
1968	Cleveland et al. (1984) [World]	21										
1969	Cleveland et al. (1984) [World]	22										
1970	Cleveland et al. (1984) [World]	22										
1971	Cleveland et al. (1984) [World]	24										
1972	Cleveland et al. (1984) [World]	23										
1973	Cleveland et al. (1984) [World]	23										
1974	Cleveland et al. (1984) [World]	7										
1975	Cleveland et al. (1984) [World]	6								Hopkins (2008) [World]	30	

1976	Cleveland et al. (1984) [World]	6								
1977	Cleveland et al. (1984) [World]	5								
1978	Cleveland et al. (1984) [World]	10								
1979	Cleveland et al. (1984) [World]	7								
1980	Cleveland et al. (1984) [World]	4								
2008									Hopkins (2008) [World]	18

Table B-6 Estimates of EROI for conventional oil production [United States]

YEAR	PRIMARY SOURCE						SECONDARY SOURCE					
	PEER REVIEWED			NON-PEER REVIEWED			PEER REVIEWED			NON-PEER REVIEWED		
	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR
1930	Cleveland (2005) [US]	100										
1935	Cleveland (2005) [US]	100										
1954	Cleveland (2005) [US]	21										
1954	Cleveland (2000) [US]	17.5										
1954	Cleveland et al. (1984) [US]	23										
1955	Cleveland (2000) [US]	18										
1957	Cleveland (2000) [US]	20										
1958	Cleveland et al. (1984) [US]	24										
1958	Cleveland (2000) [US]	19										
1959	Cleveland (2000) [US]	21										
1962	Cleveland (2000) [US]	22										
1963	Cleveland et al. (1984) [US]	28										
1963	Cleveland (2000) [US]	23										
1964	Cleveland (2000) [US]	24		Hall et al. (1986) [US]	28							
1967	Cleveland et al. (1984) [US]	30		Hall et al. (1986) [US]	30							

1967	Cleveland (2000) [US]	27						
1970	Cleveland (2000) [US]	21						
1970	Cleveland (2005) [US]	30						
1971	Cleveland (2000) [US]	30						
1972	Cleveland et al. (1984) [US]	28						
1973			Hall et al. (1986) [US]	28				
1975	Cleveland (2000) [US]	22.5					Hopkins (2008)	30
1977	Cleveland et al. (1984) [US]	19	Hall et al. (1986) [US]	20				
1980	Cleveland (2000) [US]	16						
1982	Cleveland (2000) [US]	13.5						
1983	Cleveland (2005) [US]	12						
1983	Cleveland (2000) [US]	14						
1984	Cleveland (2000) [US]	15						
1985	Cleveland (2000) [US]	15						
1987	Cleveland (2000) [US]	17						
1988	Cleveland (2000) [US]	17						
1989	Cleveland (2000) [US]	18						
1990	Cleveland (2000) [US]	18						

1992	Cleveland (2000) [US]	19								
1992	Cleveland (2005) [US]	20								
1996			Odum (1996) [North slope oil]	11.1						
1996			Odum (1996) [Mideast oil]	8.4						
1996			Odum (1996) [Texas oil]							
2007	Gately (2007) [Gulf – Offshore]	17.5	7.5							
2008									Hopkins (2008)	13

Table B-7 Estimates of EROI for conventional oil production [United Kingdom]

YEAR	PRIMARY SOURCE						SECONDARY SOURCE					
	PEER REVIEWED			NON-PEER REVIEWED			PEER REVIEWED			NON-PEER REVIEWED		
	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR
1963				Leach (1976) [UK]	5.2							
1968				Leach (1976) [UK]	8.5							
1971				Leach (1976) [UK]	9.6							
1974				National Economic Development Office (1974) [UK]	10.9							
1979				Peckham & Klitz (1979) [primary production]	84.3							
1979				Peckham & Klitz (1979) [secondary production]	71.4							
1979				Peckham & Klitz (1979) [tertiary production]	14.1							

Table B-8 Estimates of EROI for conventional oil production [Unspecified region]

YEAR	PRIMARY SOURCE						SECONDARY SOURCE					
	PEER REVIEWED			NON-PEER REVIEWED			PEER REVIEWED			NON-PEER REVIEWED		
	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR
1920							Zucchetto (2004)	50				
1935										Hopkins (2008)	100	
1945				Hall et al. (1986) [discoveries]	100							
1954				Hall et al. (1986)	24							
1959				Hall et al. (1986)	25							
1963										IFIAS (1974) from Boustead & Hancock (1979)	5.3	
1963										IFIAS (1974) from Boustead & Hancock (1979)	4.3	
1963	Chapman et al. (1974)	5.2								Chapman (1974) from Boustead &	4.2	

					Hancock (1979)	
1965			Hall et al. (1986)	100		
1968	Chapman et al. (1974)	8.5			Chapman (1974) from Boustead & Hancock (1979)	7.5
1969					Smith (1969) from Boustead & Hancock (1979)	8.3
1969					Smith (1969) from Boustead & Hancock (1979)	7
1971					Chapman (1974) from Boustead & Hancock (1979)	8.6
1972	Chapman et al. (1974)	9.6			Makhijani (1972) from Boustead &	39

			Hancock (1979)	
1972			McKilop (1972) from Boustead & Hancock (1979)	4.6
1973			Leach (1973) from Boustead & Hancock (1979)	4.7
1974			Samples (1974) from Boustead & Hancock	4.3
1975	Hall et al. (1986) [discoveries]	8	Maddox (1975) from Boustead & Hancock	8.3
1975	Hall et al. (1986) [production]	20	Leach (1975) from Boustead & Hancock (1979)	7.5
1975			Bullard (1975) from Boustead & Hancock (1979)	4.8

1976							Gartner (1976) from Boustead & Hancock (1979)	12.2
1976							Chapman (1976) from Boustead & Hancock (1979)	7.5
1976							Tuininga (1976) from Boustead & Hancock (1979)	6.7
1978	Bullard (1978)	32						
1985			Hall et al. (1986) [production]	10				
1986			Hall et al. (1986)	13				
1996								
1998					Prakash et al. (1998)	10		
1998					Gagnon (2008)	2.9		

2000	Cleveland (2005)	20						
2003						Smil (2003) [crude oil]	117	83.5
2003						Smil (2003) [refined oil]	9.7	4.7
2004			Zucchetto (2004)	12				
2007	Jones (2007)	10				Fleay (2007)	12.2	
2007			Li (2007)	9.5	1.5			
2008						Hopkins (2008)	20	
2008						Smil (2008)	117	83.5
2008						Smil (2008)	15	5
2008						Smil (2008)	10	

Table B-9 Estimates of EROI for conventional oil production [Middle East]

YEAR	PRIMARY SOURCE						SECONDARY SOURCE					
	PEER REVIEWED			NON-PEER REVIEWED			PEER REVIEWED			NON-PEER REVIEWED		
	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR
1930										Smil (2003) [Middle East]	550	450

Table B-10 Estimates of EROI for conventional oil production [California]

YEAR	PRIMARY SOURCE						SECONDARY SOURCE					
	PEER REVIEWED			NON-PEER REVIEWED			PEER REVIEWED			NON-PEER REVIEWED		
	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR
1955	Brandt (2010) [Mine mouth]	63.36	17.1									
1965	Brandt (2010) [Mine mouth]	29.5	6.56									
1975	Brandt (2010) [Mine mouth]	11.44	2.3									
1985	Brandt (2010) [Mine mouth]	6.31	1.1									
1995	Brandt (2010) [Mine mouth]	5.89	0.83									
2005	Brandt (2010) [Mine mouth]	5.18	0.75									

B.3 Unconventional oil

Table B-11 Estimates of EROI for tar sands production

YEAR	PRIMARY SOURCE						SECONDARY SOURCE					
	PEER REVIEWED			NON-PEER REVIEWED			PEER REVIEWED			NON-PEER REVIEWED		
	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR
1976										Heming (1976) [Oil sands] from Hall et al. (1986)?	3.75	0.25
1978										Resource Management Group (1978) [Oil sands] from Hall et al. (1986)?	2.05	0.15
2005										Leggett (2005) [Oil sands]	5.2	
2008							Gagnon (2008) [Oil sands]	0.7		Smil (2008) [Oil sands]	6	

Table B-12 Estimates of EROI for oil shale production

YEAR	PRIMARY SOURCE						SECONDARY SOURCE					
	PEER REVIEWED			NON-PEER REVIEWED			PEER REVIEWED			NON-PEER REVIEWED		
	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR
1975										Clerk & Varisco (1975) [Oil shale] from Hall et al. (1986)	7.62	
1975										Applied Systems Corp. (1975) [Oil shale] from Hall et al. (1986)	0.68	
1975							Gilliland (1975) [Oil shale]	2.8		Oregon Study (1975) [Oil shale] from Hall et al. (1986)	1.42	
1976										Ceri (1976) [Oil shale] from Hall et al. (1986)	6.88	

1976										Frabetti et al. (1976) [Oil shale] from Hall et al. (1986)	15.99	
1976										Ireson (1976) [Oil shale] from Hall et al. (1986)	19.7	
1977				Leach (1977) [Oil shale]	14.5					Gardiner (1977) [Oil shale] from Hall et al. (1986)	13.3	
1986				Hall et al. (1986) [Oil shale]	7	6.3						
1996				Odum (1996) [Oil shale]	0.03							
2005	Cleveland (2005) [Oil shale]	7.5	7.5									
2008	Brandt (2008) [Oil shale]	1.8	0.4									

B.4 Conventional gas

Table B-13 Estimates of EROI for conventional gas production

YEAR	PRIMARY SOURCE						SECONDARY SOURCE					
	PEER REVIEWED			NON-PEER REVIEWED			PEER REVIEWED			NON-PEER REVIEWED		
	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR
1963	Chapman et al. (1974)	2.84		Leach (1976)	2.8					Chapman (1974) from Boustead & Hancock (1979)	1.84	
1968	Chapman et al. (1974)	3.56		Leach (1976)	3.6					Chapman (1974) from Boustead & Hancock (1979)	2.56	
1970	Cleveland et al. (1984)	100										
1971				Leach (1976)	5.3					Chapman (1974) from Boustead & Hancock (1979)	4.29	
1972	Chapman et al. (1974)	5.29										

1974	Gilliland (1975)	60										
1984	Cleveland et al. (1984)	12										
1984	Cleveland et al. (1984)	15.5	7.5									
1996				Odum (1996) [On-shore]	10.3							
1996				Odum (1996) [Off-shore]	6.8							
1996				Odum (1996) [Compressed]	3.4							
1998							Prakesh et al. (1998)	23.2				
2003										Smil (2003)	56.7	21.7
2006	Shapouri et al. (2006)	16.7										
2007							Li (2007)	8.5	1.5	Fleay (2007)	14.7	

Table B-14 Estimates of EROI for electricity production from gas

YEAR	PRIMARY SOURCE						SECONDARY SOURCE					
	PEER REVIEWED			NON-PEER REVIEWED			PEER REVIEWED			NON-PEER REVIEWED		
	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR
1997	Akai et al. (1997) [LNGCC]	7.5										
1997	Akai et al. (1997) [LNGCC with CCS]	5.7	0.5									
2001				Voss (2001) [NGCC]	300							
2002							Gagnon (2002) [NGCC]	16				
2008							Lund & Biswas (2008) [NGCC]	2.35	0.2			
2008							Gagnon (2008) [NGCC]	3.8	1.3			

B.5 Unconventional gas

Table B-15 Estimates of EROI for unconventional gas production

YEAR	PRIMARY SOURCE						SECONDARY SOURCE					
	PEER REVIEWED			NON-PEER REVIEWED			PEER REVIEWED			NON-PEER REVIEWED		
	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR
1986	Hall et al. (1986) [Geo-pressurised]	3.25										
1986	Hall et al. (1986) [Geo-pressurised]	3										

B.6 Nuclear fission

Table B-16 Estimates of EROI for nuclear energy production

YEAR	**PRIMARY SOURCE**						**SECONDARY SOURCE**					
	PEER REVIEWED			NON-PEER REVIEWED			PEER REVIEWED			NON-PEER REVIEWED		
	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR
1974				Chapman & Mortimer (1974)	3.54							
1974				Chapman & Mortimer (1974)	6.08							
1974				Chapman & Mortimer (1974)	5.13							
1974				Chapman & Mortimer (1974)	6.75							
1975				Rotty et al. (1975)	4.98							
1975				Rotty et al. (1975)	4.49							
1975				Rotty et al. (1975)	6.52							

1975				Rotty et al. (1975)	2.31
1975	Rombough & Koen (1975)	5.39		Rotty et al. (1975)	3.31
1977	Chapman (1977) [MAGNOX]	15.1	3.0		
1977	Chapman (1977) [SGHWR]	11.2	2.0		
1977	Chapman (1977) [PWR]	10.2	2.0		
1977	Chapman (1977) [PWR]	15.6	2.0		
1977	Chapman (1977) [PWR]	12.9	2.0		
1977	Chapman (1977) [PWR]	16.5	2.0		
1977	Chapman (1977) [AGR]	10.5	2.0		
1977	Chapman (1977) [CANDU]	11.1	2.0		
1977	Chapman (1977) [HTR]	15.8	3.0		

1978	Bullard (1978)	100.0							
1986			Hall et al. (1986)	4					
1996			Odum (1996)	4.6					
1996			Odum (1996)	2.3					
1999	White & Kulcinski (1999)	16							
2001			Voss (2001) [PWR]	82.8					
2002					Gagnon (2002)	16	52	Meier and Kulcinski (2002)	16
2004					Zucchetto (2004)	5			
2007					Li (2007)	4.5			
2008					Gagnon (2008) [PWR]	15		Hopkins (2008)	10
2008					Kubiszweski & Cleveland (2008)	6	2		

B.7 Biomass

Table B-17 Estimates of EROI for solid biomass

YEAR	PRIMARY SOURCE						SECONDARY SOURCE					
	PEER REVIEWED			NON-PEER REVIEWED			PEER REVIEWED			NON-PEER REVIEWED		
	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR
1986				Hall et al. (1986) [standard method]	29							
1986				Hall et al. (1986) [plantation]	1.2							
1986				Hall et al. (1986) [feller-buncher-chipper]	32							
1996				Odum (1996) [Rainforest logs]	12							
1996				Odum (1996) [Spruce]	5.4							
1996				Odum (1996) [Jari pulpwood]	2.2							

1996				Odum (1996) [Brazilian wood]	3.6				
1999				Mann & Spath (1999)	15.6				
2000				WEA (2000) [Willow-Poplar hybrid]	15	5			
2000				WEA (2000) [Eucalyptus]	15	5			
2000				WEA (2000) [Miscanthus – Switch grass]	16	4			
2000				WEA (2000) [Sugar cane]	18				
2000				WEA (2000) [Rape seed]	7	3			
2000				WEA (2000) [Wood]	25	5			
2000				wEA (2000) [Sugar beet]	15	5			
2001	Matthews (2001) [Poplar, Willow]	29					Matthews (2001) [Loblolly pine]	44	2
2001	Matthews (2001) [Poplar, Willow]	24					Matthews (2001) [Poplar,	16.5	2.5

		Willow]			
2001		Matthews (2001) [Spruce]	49	8	
2001		Matthews (2001) [Poplar]	24	2	
2001		Matthews (2001) [Loblolly pine]	13	4	
2001		Matthews (2001) [Alder, Eucalyptus, Poplar, Plane]	13.5	2.5	
2001		Matthews (2001) [Poplar, Willow]	3.5	1.5	
2001		Matthews (2001) [Various]	5.5	1.5	
2001		Matthews (2001) [Various]	6	3	
2001		Matthews (2001) [Jack pine]	3		
2001		Matthews	26		

							(2001) [Willow]		
2001							Matthews (2001) [Unknown]	22	
2002							Gagnon (2002) [Plantation]	5	
2002							Gagnon (2002) [Sawmill waste]	27	
2003	Hacifero?ullari (2003) [Sugar beet]	18.5							
2003	Heller et al. (2003) [Willow at farm gate]	58.8	21.5						
2004	Volk et al. (2004) [Willow]	42	13						
2004	Heller et al. (2004) [Willow at farm gate]	55							
2005	Keoleian & Volk (2005) [Willow at farm gate]	60.1	17.4						
2007				Ismayalova (2007) [Reed	11				

				canary grass]								
2007				Ismayalova (2007) [Willow]	21							
2007				Huang (2007) [Hybrid Poplar]	7.2	1.4						
2008	Uzonoz (2008) [Sunflower seeds]	2.95								Hopkins (2008) [Sewage & Landfill gas]	40	
2008	Pan et al. (2008)	11	0.7							Hopkins (2008) [Unspecified]	30	
2008	Pan et al. (2008)	21.6	3.4				Gagnon (2008) [Biomass wastes]	27				

Table B-18 Estimates of EROI for electricity production from biomass

YEAR	PRIMARY SOURCE						SECONDARY SOURCE					
	PEER REVIEWED			NON-PEER REVIEWED			PEER REVIEWED			NON-PEER REVIEWED		
	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR
1997				Mann & Spath (1997)	16		Hall (1997)	22.9				
2001	Mann & Spath (2001) [Co-fired with coal]	5.3	0.3				Mann & Spath (2001) from Volk et al. (2003) [Wood residues – direct fired]	28.4				
2001							Mann & Spath (2001) from Volk et al. (2003) [Wood – gasified]	15.6				
2003							Heller et al. (2003) from Volk et al. (2003) [Co-fired with coal]	10.9				
2004	Heller et al. (2004) [Gasification]	13.1	0.2									

2004	Heller et al. (2004) [Direct fired]	9.9			
2006			IEA BioEnergy (2006) [IGCC]	15.61	
2006			IEA BioEnergy (2006) [Co-fired with coal]	5.3	0.2
2006			Ruark et al. (2006) [Gasification]	16	
2006			Ruark et al. (2006) [Co-fired with coal]	11	
2007			Haegele et al. (2007) [Eucalyptus]	3.2	
2008	Lund & Biswas (2008) [Biomass residues – direct fired]	27			
2008	Lund & Biswas (2008) [IGCC]	15			

Table B-19 Estimates of EROI for ethanol production from biomass

YEAR	PRIMARY SOURCE						SECONDARY SOURCE					
	PEER REVIEWED			NON-PEER REVIEWED			PEER REVIEWED			NON-PEER REVIEWED		
	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR
1980	Hopkinson & Day (1980) [Sugar-cane]	1.4	0.5									
1986				Hall et al. (1986) [Methanol from wood]	2.6							
1986				Hall et al. (1986) [Sugar-cane]	1.3	0.5						
1986				Hall et al. (1986) [Corn]	1.3							
1986				Hall et al. (1986) [Corn residues]	1.3	0.6						
1995				Shapouri et al. (1995) [Corn]	1.24							
1995				Lorenz & Morris (1995) [Corn]	2	0.6						

1995				Lorenz & Morris (1995) [Cellulosic ethanol]	2.6		
1996				Odum (1996) [Sugar-cane]	1.14		
1997	Giampietro et al. (1997) [Temperate]	1.1	0.6			Hall (1997) [Wheat]	4.74
1997	Giampietro et al. (1997) [Tropical]	2.8	0.3			Hall (1997) [Sugar-beet]	12.21
1997						Hall (1997) [Rape]	4.98
1997						Hall (1997) [Methanol from wood]	13.33
1998	McLaughlin & Walsh (1998) [Corn]	1.2					
1998	McLaughlin & Walsh (1998) [Switch-grass]	4.43					
1998	Prakash et al. (1998) [Corn]	1.1					

1998	Prakash et al. (1998) [Sugar-cane]	2.4			
1998	Prakash et al. (1998) [Cassava]	1.5			
1998	Prakash et al. (1998) [Sorghum]	1.9			
1998	Prakash et al. (1998) [Sugar-beet]	1.1			
1998	Prakash et al. (1998) [Grain]	1.4			
2000			Alberta Grain Commission (2000)	2.3	0.3
2004			Shapouri et al. (2004) [Corn]	1.67	
2004			IEA (2004) [Corn]	0.9	0.2
2004			IEA (2004) [Sugar-cane]	8.3	1.9
2005	Pimental & Patzek (2005) [Switch-grass]	0.69			

2005	Pimental & Patzek (2005) [Corn]	0.81	0.03					
2005	Pimental & Patzek (2005) [Cellulosic from wood]	0.64						
2006	Shapouri et al (2006) [Replacement method]	1.3				Hammerschlag (2006)	1.4	0.3
2006	Shapouri et al (2006) [Aspen method]	1.67				Hammerschlag (2006) [Cellulosic]	5.2	1.2
2006	DeWulf & Langenhove (2006)	3.1				Glaser (2006) [Cellulosic ethanol]	5.5	1.1
2006	DeWulf & Langenhove (2006) [Corn]	4.17				Glaser (2006) [Corn]	1.2	0.4
2006	Hill et al. (2006) [Corn]	1.25						
2007	Jones (2007) [Corn]	2		Ismayalova (2007) [Corn]	1.34	von Blottnitz & Curran (2007) [Sugar-cane, Brazil]	7.9	

2007	Lavigne & Powers (2007) [Corn]	1.1	Ismayalova (2007) [Poplar]	2.62	von Blottnitz & Curran (2007) [Sugar-beet, UK]	2.0	
2007	Lavigne & Powers (2007) [Corn with stover]	1.7			von Blottnitz & Curran (2007) [Corn, US]	1.3	
2007					von Blottnitz & Curran (2007) [Molasses, India]	48.0	
2007					von Blottnitz & Curran (2007) [Molasses, SA]	1.1	
2007					von Blottnitz & Curran (2007) [Corn stover, US]	5.2	
2007					von Blottnitz & Curran (2007) [Wheat straw, UK]	5.2	
2007					von Blottnitz & Curran (2007) [Bagasse, India]	32.0	
2007					Li (2007)	1.3	0.6

2008	Vadas et al. (2008) [Switch-grass]	11.0	0.3	Porter et al. (2008) [Corn]	1.28					Hopkins (2008)	2	
2008	Vadas et al. (2008) [Alfalfa]	3.0	0.1	Coughlin & Fridley (2008) [Cellulosic]	3.7	2.1				Hopkins (2008) [Sugar-cane]	6	2
2008	Vadas et al. (2008) [Corn]	1.4								Hopkins (2008) [Corn]	1.2	0.4
2008	Vadas et al. (2008) [Corn with stover]	2.2								Yuan et al. (2008) [Corn]	2.3	0.8
2008	Dong et al. (2008) [Wheat, China]	1.1								Yuan et al. (2008) [Sugar-cane]	3.5	0.5
2008	Dong et al. (2008) [Corn]	1.2								Yuan et al. (2008) [Sugar-beet]	3.0	0.5
2008										Yuan et al. (2008) [Sorghum]	7.5	2.5
2008										Yuan et al. (2008) [Miscanthus]	42.5	27.5
2008										Yuan et al. (2008) [Switch-grass]	30.0	20.0

2008										Yuan et al. (2008) [Poplar]	15.0	5.0
2009	Piccolo & Bezzo (2009) [Cellulosic - method 1]	3.8										
2009	Piccolo & Bezzo (2009) [Cellulosic - method 2]	2.6										
2009	Liska et al. (2009)	1.6	0.3									

Table B-20 Estimates of EROI for diesel production from biomass

YEAR	PRIMARY SOURCE						SECONDARY SOURCE					
	PEER REVIEWED			NON-PEER REVIEWED			PEER REVIEWED			NON-PEER REVIEWED		
	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR
1997	Giampetrio et al. (1997)	1	0.4									
1998				Sheenan et al. (1998) [Soybean]								
2002	Kallivroussis et al. (2002) [Sunflower]	4	0.6									
2003	Cardone et al. (2003) [Brassica]	1.4	0.3				Venturi & Venturi (2003) [Sunflower]	0.6	0.3			
2003							Venturi & Venturi (2003) [Rape-seed]	0.9	0.2			
2003							Venturi & Venturi (2003) [Soybean]	0.4	0.2			
2003							Venturi & Venturi (2003) [Sunflower]	0.8	0.4			

2003							Venturi & Venturi (2003) [Rape-seed]	1.3	0.3
2003							Venturi & Venturi (2003) [Soybean]	1.2	0.5
2004	Bernesson et al. (2004) [Rape]	3.1	0.5						
2004	Janulis (2004)	1.3	0.2						
2005	Giampetrio & Ulgiati (2005)	1.2	0.2						
2005	Pimental & Patzek (2005) [Soybean]	0.86	0.07						
2006	Hill et al. (2006) [With co-products]	3.7		Bennett (2006) [Canola]	2.4	0.9			
2006	Hill et al. (2006) [Without co-products]	1.9		Bennett (2006) [Mustard – method 1]	3.4	1.3			
2006				Bennett (2006) [Mustard – method 2]	2.5	1.0			
2007	Jones (2007)	3							

2008	Prueksakorn & Gheewala (2008) [Jatropha with co-products]	7	5	Yuan et al. (2008) [Soybean]	0.4	0.2	Hopkins (2008)	2
2008	Prueksakorn & Gheewala (2008) [Jatropha without co-products]	1.6	1.1	Yuan et al. (2008) [Canola]	0.9	0.2		
2008	Pradhan et al. (2008) [Soybean]	2.6	0.4	Yuan et al. (2008) [Sunflower]	0.6	0.3		

B.8 Hydro

Table B-21 Estimates of EROI for hydro energy production

YEAR	PRIMARY SOURCE						SECONDARY SOURCE					
	PEER REVIEWED			NON-PEER REVIEWED			PEER REVIEWED			NON-PEER REVIEWED		
	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR
1986				Hall et al. (1986)	11.2							
1986				Hall et al. (1986)	22.5	12.5						
1996				Odum (1996)	10							
2001				Voss (2001)	22							
2002							Gagnon (2002) [Reservoir]	165	115			
2002							Gagnon (2002) [Run-of-river]]	150	120			
2007							Li (2007)	10		Pacca & Horvath (2002) from Haegele (2007)	30.9	
2008							Kubiszewski & Cleveland (2008)	12	6	Hopkins (2008) [Small hydro]	32	
2008							Lund & Biswas (2008) [Reservoir]	154	106	Hopkins (2008) [Large hydro]	23	

2008	Lund & Biswas (2008) [Run-of-river]	148.5	118.5	
2008	Gagnon (2008) [Reservoir]	242.5	37.5	
2008	Gagnon (2008) [Run-of-river]	218.5	48.5	
2008	Allen et al. (2008)	93		

B.9 Geothermal

Table B-22 Estimates of EROI for geothermal energy production

YEAR	PRIMARY SOURCE						SECONDARY SOURCE					
	PEER REVIEWED			NON-PEER REVIEWED			PEER REVIEWED			NON-PEER REVIEWED		
	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR
1975	Gilliland (1975) [Dry steam]	3.6										
1975	Gilliland (1975) [Flash steam]	3.1										
1979				Herendeen (1979)	14					Herendeen & Anderson (1979) [Liquid – high turbine] from Fazzolare & Smith (1979)	18	1.2
1979										Herendeen & Anderson (1979) [Liquid – low turbine] from Fazzolare & Smith (1979)	16.3	1

1979	Herendeen & Anderson (1979) [Hot dry rock] from Fazzolare & Smith (1979)	21.75	0.95
1979	Herendeen & Anderson (1979) [Binary] from Fazzolare & Smith (1979)	14.1	0.5
1979	Herendeen & Anderson (1979) [Liquid – high turbine] from Fazzolare & Smith (1979)	17.7	1.1
1979	Herendeen & Anderson (1979) [Liquid – low turbine] from Fazzolare & Smith (1979)	16.15	0.85

1979			Herendeen & Anderson (1979) [Hot dry rock] from Fazzolare & Smith (1979)	21.65	1.15
1979			Herendeen & Anderson (1979) [Binary] from Fazzolare & Smith (1979)	13.65	0.55
1981	Icerman (1981)	1.8	Halloran (1981) [Hot dry rock] from Halloran (2007)	2.1	
1981	Herendeen & Plant (1981) [Dry steam]	13			
1981	Herendeen & Plant (1981) [Flash steam]	4.4			
1981	Herendeen & Plant (1981) [Hot dry rock binary]	2.7			

1981	Herendeen & Plant (1981) [Hot dry rock binary]	3.4					
1981	Herendeen & Plant (1981) [Hot dry rock binary]	3.9					
1981	Herendeen & Plant (1981) [Hot dry rock binary]	1.9					
1981	Herendeen & Plant (1981) [Hot dry rock binary]	13					
1983						Halloran (1983) [Dry steam] from Halloran (2007)	3.1
1986			Hall et al. (1986)	4			
1986			Hall et al. (1986)	7.45	5.55		

1991						Halloran (1991) [Dry steam] from Halloran (2007)	5.9
1996	Odum (1996)	7.9					
2007	Halloran (2007) [Hot dry rock]	7.8					
2007	Halloran (2007) [Hot dry rock]	6.6					
2008			Kubiszewski & Cleveland (2008)	8	6	Hopkins (2008)	8

B.10 Tidal

Table B-23 Estimates of EROI for tidal energy production

YEAR	PRIMARY SOURCE						SECONDARY SOURCE					
	PEER REVIEWED			NON-PEER REVIEWED			PEER REVIEWED			NON-PEER REVIEWED		
	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR
1996			Odum (1996)	15					1996			Odum (1996)
2008							Hopkins (2008) [Tidal range]	87	2008			
2008							Hopkins (2008) [Tidal stream]	17	2008			

B.11 Wind

Table B-24 Estimates of EROI for wind energy production

YEAR	PRIMARY SOURCE						SECONDARY SOURCE					
	PEER REVIEWED			NON-PEER REVIEWED			PEER REVIEWED			NON-PEER REVIEWED		
	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR
1997				WindPowerNote (1997)	33.9							
1998				White & Kulcinski (1998)	17							
2000	White & Kulcinski (2000)	23										
2001				Mathur & Bansal (2001)	9.6							
2001				Mathur & Bansal (2001)	11.1							
2001				Mathur & Bansal (2001)	31.1							
2001				Voss (2001)	37.5							
2002	Mathur et al. (2002)	20.4					Gagnon (2002)	43				

2002							Meier & Kulcinski (2002)	23
2004					Wagner & Pick (2006)	17.8		
2004					Heller et al. (2004)	30.3		
2007					Li (2007)	2		
2008	Lund & Biswas (2008)	34			Kubeszweski & Cleveland (2008)	19.8	Hopkins (2008)	11
2008	Lund & Biswas (2008)	18			Gagnon (2008) [Onshore]	34		
2008	Allen et al. (2008) [Open 'micro' turbine]	8.8			Gagnon (2008) [Offshore]	17		
2008	Allen et al. (2008) [Urban 'micro' turbine]	1.7			Allen et al. (2008) [Offshore]	16.0		
2008					Allen et al. (2008) [Onshore]	19.0		
2008					Allen et al. (2008) ['Micro' turbine]	3.9		

2009	Martinez et al.	34.4						
1997			WindPowerNote (1997)	33.9				
1998			White & Kulcinski (1998)	17				
2000	White & Kulcinski (2000)	23						
2001			Mathur & Bansal (2001)	9.6				
2001			Mathur & Bansal (2001)	11.1				
2001			Mathur & Bansal (2001)	31.1				
2001			Voss (2001)	37.5				
2002	Mathur et al. (2002)	20.4			Gagnon (2002)	43		
2002							Meier & Kulcinski (2002)	23
2004					Wagner & Pick (2006)	17.8		
2004					Heller et al. (2004)	30.3		

2007					Li (2007)	2		
2008	Lund & Biswas (2008)	34			Kubeszweski & Cleveland (2008)	19.8	Hopkins (2008)	11
2008	Lund & Biswas (2008)	18			Gagnon (2008) [Onshore]	34		
2008	Allen et al. (2008) [Open 'micro' turbine]	8.8			Gagnon (2008) [Offshore]	17		
2008	Allen et al. (2008) [Urban 'micro' turbine]	1.7			Allen et al. (2008) [Offshore]	16.0		
2008					Allen et al. (2008) [Onshore]	19.0		
2008					Allen et al. (2008) ['Micro' turbine]	3.9		
2009	Martinez et al.	34.4						

B.12 Solar

Table B-25 Estimates of EROI for solar thermal energy production

YEAR	PRIMARY SOURCE						SECONDARY SOURCE					
	PEER REVIEWED			NON-PEER REVIEWED			PEER REVIEWED			NON-PEER REVIEWED		
	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR
1976	Zucchetto & Brown (1977)	1.8	0.6									
1986				Hall et al. (1986) [Flat plate]	1.9							
1999	Mathur & Bansal (1999)	16.2	11.2									
2001	Mathur & Bansal (2001)	6	1.7									
2002	Mathur et al. (2002)	4.7	2.4									
2004				Streicher et al. (2004)	12	3.3						
2008							Kubiszewski & Cleveland (2008)	4	3	Hopkins (2008)	10	

Table B-26 Estimates of EROI for PV energy production

YEAR	PRIMARY SOURCE						SECONDARY SOURCE					
	PEER REVIEWED			NON-PEER REVIEWED			PEER REVIEWED			NON-PEER REVIEWED		
	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR
1977				Lindmayer (1977) [PV]	4.7	1.6						
1986				Hall et al. (1986) [PV]	5.9	4.2						
1986				Hall et al. (1986) [PV]	5.5	4.5						
1991							Hyne et al. (1991) from Azzopardi & Mutale (2010) [CuInSe2]	19.09	5.01			
1996	Wilson & Young (1996) [PV]	2.2	0.7	Odum (1996) [PV]	0.48							
1996				Odum (1996) [PV]	0.36							
1997							Sherwani et al. (2010) [MC Si]	1.29				

1998	Kato et al. (1998) from Azzopardi & Mutale (2010) [MC & SC Si]	8.33	3.91
1998	Frankl et al. (1998) from Azzopardi & Mutale (2010) [SC Si]	2.78	
2000	Alsema et al. (2000) from Azzopardi & Mutale (2010) [MC Si]	8.75	1.25
2000	Alsema et al. (2000) from Azzopardi & Mutale (2010) [Amorphous Si]	9.75	2.25
2000	Sherwani et al. (2010) [Amorphous]	11.11	
2000	Sherwani et al. (2010) [MC Si]	9.38	

2001	Mathur & Bansal (2001) [PV]	2.2	0.5	Mathur (2001) [PV]	1.5	0.1			
2001	Knapp & Jester (2001) [PV]	10.5	3.5	Frankl (2001) [PV array]	8.9				
2001				Frankl (2001) [PV]	1.5	0.5			
2001				Voss (2001) [PV polymorphous]	1.7				
2001				Voss (2001) [PV amorphous]	3.2				
2002	Mathur et al. (2002) [PV]	0.8	0.2	Meier (2002) [PV – thin film]	5.7				
2002	Pehnt (2002) [PV]	9.2	4.8	Meier & Kulcinski (2002) [PV]	6		Gagnon (2002) [PV]	9	7
2003	Keoleian & Lewis (2003) [PV – building integrated]	4.5	0.6						
2003							Sherwani et al. (2010) [PC Si]	17.65	

2004							Jungbluth et al. (2004) from Azzopardi & Mutale (2010) [Amorphous Si]	7.5	2.5
2004							Rhyd & Sanden (2004) [PV]	6.1	3.9
2004							Heller et al. (2004)	43	
2005	Peharz & Dimroth (2005) [PV – concentrator]	21.9	4.8				Pro et al. (2005)	14	9
2005							Sherwani et al. (2010) [PC Si]	6.06	
2005							Sherwani et al. (2010) [PC Si]	6.9	
2006				Veltkamp (2006) [Dye-sensitised cells – panel]	66.67	50			
2006				Veltkamp (2006) [Dye-sensitised cells – BOS]	25	8.97			
2006							Sherwani et al. (2010) [MC Si]	3.75	

2006				Sherwani et al. (2010) [MC Si]	4.26			
2006				Sherwani et al. (2010) [MC Si]	5.59			
2006	Mason et al. (2006) [PV – array]	74.6	20.6			Watt (2006) [PV – thin film]	6.2	1.2
2006	Kannan et al. (2006) [PV]	3.4				Watt (2006) [PV – Multi-junction Si]	5.7	0.6
2006	Fthenakis & Alsema (2006) [PV – Multi-junction Si]	9.1						
2006	Fthenakis & Alsema (2006) [PV – CdTe rooftop]	20						
2006	Fthenakis & Alsema (2006) [PV – CdTe ground]	18.2						
2007	Pacca et al. (2007) [PV – thin film]	8.7	1.5					

2007	Pacca et al. (2007) [PV – multicrystalline]	3.9	0.6			
2007	Richards & Watt (2007) [PV]	7.3	2.1			
2007	Richards & Watt (2007) [PV]	4	1.2			
2007				Raugei et al. (2007) from Azzopardi & Mutale (2010) [CdTe]	13.33	
2007				Raugei et al. (2007) from Azzopardi & Mutale (2010) [CIS]	7.14	
2007				Raugei et al. (2007) from Azzopardi & Mutale (2010) [MC Si]	8	1.39

2007							Roes et al. (2007) from Azzopardi & Mutale (2010) [Polymer]	26.88				
2007							Sherwani et al. (2010) [Amorphous]	6.25				
2007							Sherwani et al. (2010) [PC Si]	3.51				
2008							Sherwani et al. (2010) [PC Si]	15.79				
2008							Sherwani et al. (2010) [PC Si]	20				
2008							Sherwani et al. (2010) [Amorphous]	12				
2008	Tovey (2008) [PV – array]	4.7	0.4				Lund & Biswas (2008) [PV]	7.5	1.5	Hopkins (2008) [PV]	3.4	0.9
2008							Gagnon (2008) [PV]	4.5	1.5	Hopkins (2008) [PV]	9	
2008							Allen et al. (2008) [PV]	2.9				
2008							Kubiszewski & Cleveland (2008)	8	7			

2009	Kaldellis et al. (2009) [SC Si, Stand-alone system]	1.43	0.48
2009	Kaldellis et al. (2009) [MC Si, Stand-alone system]	1.67	0.56
2009	Kaldellis et al. (2009) [Amorphous Si, Stand-alone system]	1.2	0.33
2009	Kaldellis et al. (2009) [CdTe, Stand-alone system]	1.9	0.6
2010	Zhai & Williams (2010)	9.58	4.7
2010	Nishimura et al. (2010) [hcPV in Gobi]	10	
2010	Nishimura et al. (2010) [hcPV in Toyohashi]	7.58	

2010	Nishimura et al. (2010) [MC Si in Gobi]	11.56										
2010	Kaldellis et al. (2010) [Stand-alone system]	4.52	1.19									
2010	Kaldellis et al. (2010) [Grid connected system]	6.5	1.5									
2010	Azzopardi & Mutale (2010)	18.75	2.08									

Table B-27 Estimates of EROI for STEC energy production

YEAR	**PRIMARY SOURCE**						**SECONDARY SOURCE**					
	PEER REVIEWED			NON-PEER REVIEWED			PEER REVIEWED			NON-PEER REVIEWED		
	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR
1986				Hall et al. (1986)	4.2							
										Hopkins (2008)	18	

B.13 Wave

Table B-28 Estimates of EROI for wave energy production

YEAR	PRIMARY SOURCE						SECONDARY SOURCE					
	PEER REVIEWED			NON-PEER REVIEWED			PEER REVIEWED			NON-PEER REVIEWED		
	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR
2006	Banjeree (2006)	20							2006	Banjeree (2006)	20	
2008							Hopkins (2008)	15	2008			

B.14 OTEC

Table B-29 Estimates of EROI for OTEC energy production

YEAR	PRIMARY SOURCE						SECONDARY SOURCE					
	PEER REVIEWED			NON-PEER REVIEWED			PEER REVIEWED			NON-PEER REVIEWED		
	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR	AUTHOR	MEAN EROI	ERROR
1979				Carlson (1979)	3.74	2						
1979				Perry et al. (1979)	8.5	1.5						
1996				Odum (1996)	1.5							
2000	Odum (2000)	1.4										

APPENDIX C. ESTIMATES OF POTENTIAL RESOURCES

C.1 Coal

Table C-1 Estimates of ultimately recoverable resources of coal

YEAR	AUTHOR	AFFILIATION	ULTIMATELY RECOVERABLE (Gtonnes) unless stated	MEAN RECOVERABLE (EJ)	ERROR (EJ)
1913		IGC Toronto†		20,926	0
1913		IGC Toronto†		19,665	0
1936		WPC Yearbook†		31,799	0
1948		WPC Yearbook†		20,105	0
1960		WPC Yearbook†		23,446	0
1962		WPC Survey†		22,538	0
1968		WPC Survey†		21,160	0
1972	(Armstrong)		4400	128,953	0
1974	(Thomas)		7600	222,738	0
1974		(WEC)	591	17,321	0
1977	(McMullen, Morgan, & Murray)		411	12,042	0
1977	(McMullen, et al.)		137	4,015	0
1977		(MIT)	12000 (Bboe)	73,440	0
1978		WEC Delphi Poll‡	636	18,640	0
1978	(Ezra)		343	14,361	0
1978		US Dept Energy (in Ezra 1978)	645 at 10% recovery	27,005	0
1978		US Dept Energy (in Ezra 1978)	3225 at 50% recovery	135,024	0
1978	(Ezra)		640	18,757	0
1979		WEC	3000	87,923	0
1979	(Fettweis)		700	20,515	0
1979	(Fettweis)		600	17,585	0
1979	(Fettweis)		1025	30,040	0

YEAR	AUTHOR	AFFILIATION	ULTIMATELY RECOVERABLE (Gtonnes) unless stated	MEAN RECOVERABLE (EJ)	ERROR (EJ)
1979	(Fettweis)		330	9,672	0
1979	(Parker)		5000	146,538	0
1980	(P. King)		600	17,585	0
1981	(Wolf Häfele)		637	18,669	0
1982	(Fraas)		53.2 (ZJ)	53,200	0
1982	Hafele		2400 (TWyr)	75,738	0
1985	(J. Edmonds & Reilly)		693.27	20,318	0
1986	(Prasad)		431	12,628	0
1986		(WEC)	Bit. 404, Sub-bit. 162, Lignite: 272	25,940	0
1992	(Starr, Milton, & Alpert)			26,500	0
1992	(Nathwani, Siddal, & Lind)		1327 (TWyr)	41,877	0
1995	(R. Hill, O'Keefe, & Snape)		1083	31,740	0
1995		(WEC)	22941-37390 (EJ)	30,166	7225
1995		(Shell)	17000-23000 (EJ)	20,000	3000
2006	(Rempel, Schmidt, & Schwarz-Schampera, 2006)	BGR		28,993	0
2007	(Chu & Goldemberg)	InterAcademy Council	26271 (EJ)	26,271	0
2007		(WEC)	847.488	24,838	0
2008		(EIA)		33,931	0

† Estimates from (M. Grenon, 1979),

‡ Estimates from (Michel Grenon, 1978)

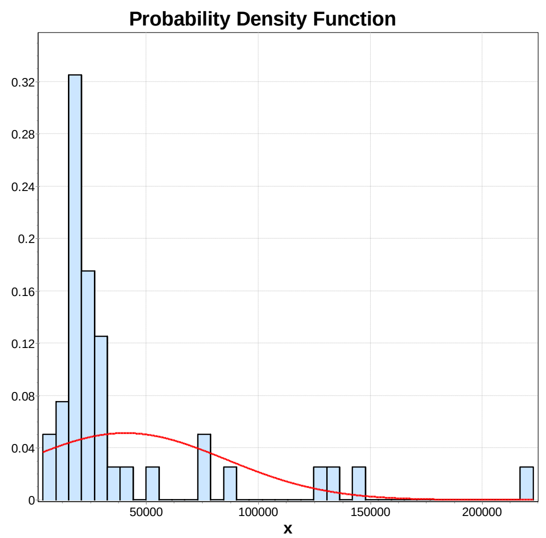


Figure C-1 Histogram of estimates of ultimately recoverable resources of coal with normal distribution for comparison

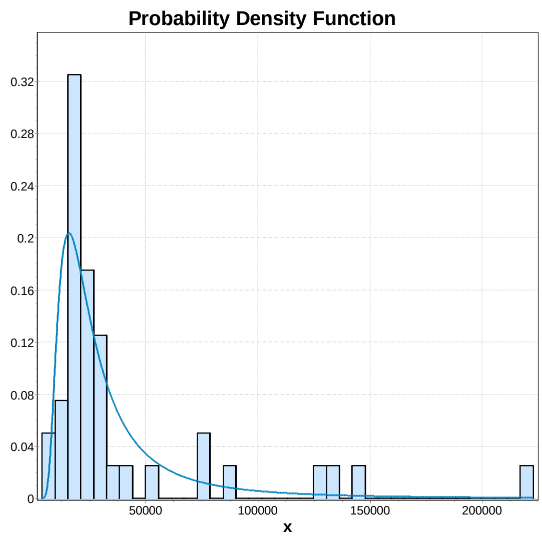


Figure C-2 Histogram of estimates of ultimately recoverable resources of coal with general extreme value (GEV) distribution for comparison

Table C-2 Goodness-of-fit statistics for normal and GEV distributions to estimates of ultimately recoverable resources of coal

DISTRIBUTION		DEGREES OF FREEDOM	STATISTIC	P-VALUE
Normal	Kolmogorov-Smirnov	-	0.33595	1.5763E-4
	Anderson-Darling	-	5.7422	-
	Chi-Squared	2	19.693	5.2926E-5
GEV	Kolmogorov-Smirnov	-	0.13729	0.40167
	Anderson-Darling	-	0.99733	-
	Chi-Squared	4	4.0985	0.39283

C.2 Conventional Oil:

Table C-3 Estimates of the ultimately recoverable resources of conventional oil

YEAR	AUTHOR	AFFILIATION	ULTIMATELY RECOVERABLE (Billion Barrels unless stated)	MEAN RECOVERABLE (Billion Barrels)	ULTIMATELY RECOVERABLE (EJ)	ERROR (EJ)
1942	Pratt, Weeks & Stebinger‡		600	600	3672	0
1946	Duce†	Aramco	400 - 500	450	2754	306
1946	Pogue†		555 - 615	585	3580	184
1948	Weeks†	EXXO	610 - 617	614	3755	21
1949	Levorsen†	Stanford	1500 - 1635	1568	9593	413
1949	Weeks†	Exxon	1010 - 1015	1013	6197	15
1952	Pratt†		650	650	3978	0
1953	MacNaughton‡		1000	1000	6120	0
1956	Hubbert†		1250	1250	7650	0
1958	Weeks†	Exxon	1500 - 3000	2250	13770	4590
1959	Weeks†	Exxon	2000 - 3500	2750	16830	4590
1965	Weeks†		1250	1250	7650	0
1965	Hendricks†	USGS	1984 – 2000 - 2480	2000	12240	49
1967	Ryman†	Esso	2090	2090	12791	0
1968		Shell‡	1800	1800	11016	0
1968	Weeks†		2200 - 3350	2775	16983	3519
1969	Hubbert†	Shell/USGS	1350 - 2100	1725	10557	2295
1970	Moody†	Mobil	1800	1800	11016	0
1971	Warman‡	BP	1200 – 2000	1600	9792	2448
1971	Weeks†		2290 - 3490	2890	17687	3672
1972		ESSO^	2100	2100	12852	0
1972	Warman†	BP	1200-2000	1600	9792	2448
1972	Jodry°	Sun	1952	1952	11946	0
1972	Moody& Emmerich[d]	Mobil	1800-1900	1850	11322	612
1972	Bauquis et al†	IFP	1900	1900	11628	0

YEAR	AUTHOR	AFFILIATION	ULTIMATELY RECOVERABLE (Billion Barrels unless stated)	MEAN RECOVERABLE (Billion Barrels)	ULTIMATELY RECOVERABLE (EJ)	ERROR (EJ)
1972		Report to UN Conference^	2500	2500	15300	0
1972	Moody~		1800	1800	11016	0
1973	Odell†	Erasmus	4000	4000	24480	0
1973	Schweinfurth†	USGS	2950	2950	18054	0
1973	Hubbert†		2000	2000	12240	0
1973	Linden~	Inst. Gas Tech,	2850	2850	17442	0
1974	Hubbert†		1800-2100	1950	11934	918
1974	(Thomas)		1800	1800	11016	0
1974	Kirkby & Adams†	BP	1600 - 2000	1800	11016	1200
1974	Bonnillas[a]	SOCAL	2000	2000	12240	0
1974		SPRU, UK^	1800-2480	2140	13097	2100
1974	Howitt[a]	BP	1750	1750	10710	0
1974	Parent & Linden†		3000-4000	3500	21420	3060
1975	MacKay & North[h]		1000-1050	1025	6273	306
1975	Moody & Esser†	Mobil	1312–2000–3237 (95%-mean–5%)	2000	12240	2110
1975	Moody & Geiger†		2000	2000	12240	0
1975	Adams & Kirkby†		2000	2000	12240	0
1975	MacKay, North†		1100-1400	1250	7650	918
1975	Moody & Esser[d]	Moody	1705–2030–2505 (95%-mean–5%)	2030	12424	1025
1975		National Academy of Science (in Pierce 2007)	2100	2100	12852	0
1975	Odell & Rosing†		4000	4000	24480	0

YEAR	AUTHOR	AFFILIATION	ULTIMATELY RECOVERABLE (Billion Barrels unless stated)	MEAN RECOVERABLE (Billion Barrels)	ULTIMATELY RECOVERABLE (EJ)	ERROR (EJ)
1975		Exxon[d]	1948	1948	11922	0
1976	Folinsbee~		1800	1800	11016	0
1976		Am. Petr. Inst.[g]	2050	2050	12546	0
1976	Grossling †	USGS	method 1: 1960–5600	3780	23134	11100
1976	Grossling †	USGS	method 2: 2200–3000	2600	15912	2450
1976	Klemme°	Weeks	1600	1600	9792	0
1976	Barthel†	BGR	2500	2500	15300	0
1976	Styrikovich[h]		5100-5500	5300	32436	1530
1977	(McMullen, et al.)		2 (1E+22 joules)	3268	20000	0
1977		WEC[a]	2250	2250	13770	0
1977	Parent & Linden°	IGT	2130 - 2480	2305	14107	1070
1977		(MIT)	2000	2000	12240	0
1977	DELPHI*	IFP	1240 (low group mean)	1240	7589	0
1977	DELPHI*	IFP	1799 (mid group mean)	1799	11010	0
1977	DELPHI*	IFP	3050 (high group mean)	3050	18666	0
1977	DELPHI*	IFP	2117 (poll mean)	2117	12956	0
1977	Nelson~	SOCAL	2000	2000	12240	0
1977	Hubbert^		2000	2000	12240	0
1977	Folinsbee†		1700	1700	10404	0
1977	Ehrlich et al^		1900	1900	11628	0
1977	Klemme†		1750	1750	10710	0
1977	Seidl†	IIASA	4100-5900	5000	30600	5508
1977	Styrikovich†		6000-11000 (all liquids)	8500	52020	15300
1977		WEC†	2300	2300	14076	0

YEAR	AUTHOR	AFFILIATION	ULTIMATELY RECOVERABLE (Billion Barrels unless stated)	MEAN RECOVERABLE (Billion Barrels)	ULTIMATELY RECOVERABLE (EJ)	ERROR (EJ)
1977	Despairies[h]		1600-2500-7300	2500	15300	8721
1978		WEC IFP [e]	1803	1803	11034	0
1978		WEC Delphi Poll[i]	175-240-350 (10-66-75%) (Gtonnes)	1471	9002	3666
1978	(Ezra)		90 (Gtonnes)	620	3768	0
1978		Dept Energy (in Ezra 1978)	233 (Gtonnes)	1600	9755	0
1978	Warman (in Ezra 1978)		270 (Gtonnes)	1850	11304	0
1978	Moody†	Moody	2030	2030	12424	0
1978	Weeks [g]		3600	3600	22032	0
1978	DeBruyne[a]	Shell	1600	1600	9792	0
1978	Klemme†		1750	1750	10710	0
1978	Styrikovich[g]	USSR Academy of Science	6000	6000	36720	0
1978	Nehring†	Rand	1700 – 2000 – 2300	2000	12240	918
1979		(WEC)	2.58 (1E+11 tonnes)	0	10802	0
1979	Halbouty†		2200	2200	13464	0
1979	Halbouty and Moody*		1421–2128–3556 (95%-mean–5%)	2128	13023	2160
1979	Nehring†	Rand	1600-2000	1800	11016	1224
1979	Roorda[a]	Shell	2400	2400	14688	0
1979	Meyerhoff†		2200	2200	13464	0
1979	Wood[h]	Cities Services	1500-2200-3100	2200	13464	2448
1979	Bois et al[h]	French Petroleum Inst.	2340	2340	14321	0
1979		Exxon[h]	1350-1850	1600	9792	1530
1980		WEC†	2600	2600	15912	0
1980	DeBruyne†		1500	1500	9180	0
1980	Parent†	Inst. Gas Tech,	2053-2446	2250	13767	1203

YEAR	AUTHOR	AFFILIATION	ULTIMATELY RECOVERABLE (Billion Barrels unless stated)	MEAN RECOVERABLE (Billion Barrels)	ULTIMATELY RECOVERABLE (EJ)	ERROR (EJ)
1980	Schubert†	West German Geol. Survey and WEC	2584	2584	15814	0
1980	Odell & Rosing	Erasmus	2000-6000	4000	24480	12240
1981	Qadeer		2000-3000	2500	15300	0
1981	Strickland[a]	Conoco	2100	2100	12852	0
1981	Colitti[a]	AGIP	2100	2100	12852	0
1981	Halbouty†		2250	2250	13770	0
1981	Hubbert & Root [g]		2000	2000	12240	0
1981		World Bank^	1900	1900	11628	0
1982	(Fraas)		14.2 (ZJ)	2320	14200	0
1982	Hafele		420 (TWyr)	2170	13254	0
1982	Nehring~	Rand	2350	2350	14382	0
1983	Odell & Rosing†		3000	3000	18360	0
1983	Masters & Root†	USGS	1700	1700	10404	0
1984	Martin~	BP	1700	1700	10404	0
1984	Ivanhoe[a]		1700	1700	10404	0
1984	Masters†		1600-2300	1950	11934	2142
1985	Martin†		1700	1700	10404	0
1985	(J. Edmonds & Reilly)		2194	2194	13427	0
1986		(WEC)	91500 (Mtonnes)	630	3831	0
1987	(Khan)		354 (Gtonnes)	2420	14819	0
1987	Masters†	USGS	1750	1750	10710	0
1987	Jenkins [g]	BP	1700	1700	10404	0
1989	Campbell†		1700	1700	10404	0
1989	Bookout†	Shell	2000	2000	12240	0
1991	Campbell†		1650	1650	10098	0
1991	Masters†		2200	2200	13464	0

YEAR	AUTHOR	AFFILIATION	ULTIMATELY RECOVERABLE (Billion Barrels unless stated)	MEAN RECOVERABLE (Billion Barrels)	ULTIMATELY RECOVERABLE (EJ)	ERROR (EJ)
1992	(Nathwani, et al.)		252 (TWyr)	1300	7953	0
1992	Meadows et al [e]		1800-2500	2150	13158	2140
1992	Montadert & Alazard[c]		2200	2200	13464	0
1992	Campbell†		1700	1700	10404	0
1993	Campbell†		1700	1700	10404	0
1993		OPEC	2150	2150	13158	0
1993	Laherrere†		1700	1700	10404	0
1993	Townes[a]		3000	3000	18360	0
1993	(Masters)	USGS	2100-2300-2800 (95%-mean-5%)	2300	14076	612
1994	Masters[a]		2300	2300	14076	0
1994	Masters†		2200	2200	13500	0
1994	Campbell†		1700	1700	10404	0
1995	Mabro[c]		1800	1800	11016	0
1995	Laharrere[b]		1750	1750	10710	0
1995	Campbell†		1800	1800	11016	0
1995	Riva [g]		2300	2300	14076	0
1995		Petroconsultants, '95^	1800 (excluding NGL)	1800	11016	0
1996	Mackenzie†	Researcher	1800-2600	2200	13464	2448
1997	Invanhoe^	Consultant	2000	2000	12240	0
1997	Edwards^	University of Colorado	2836	2836	17356	0
1997	Campbell†	Consultant	1800–2000	1900	11628	612
1997	Laherrere [e]		2700 (all liquids)	2700	16524	0
1998	Perrodon & Laherrere [g]		2750 (all liquids)	2750	16830	0
1998		IEA WEO 1998^	2300	2300	14076	0

YEAR	AUTHOR	AFFILIATION	ULTIMATELY RECOVERABLE (Billion Barrels unless stated)	MEAN RECOVERABLE (Billion Barrels)	ULTIMATELY RECOVERABLE (EJ)	ERROR (EJ)
1998		(IEA)	2800	2800	17136	0
1998		(EIA)	4700	4700	28764	0
1998		(WEC)		1860	11400	0
1998	(Colin J. Campbell & Laherrere)		1800	1800	11016	0
1998		BP (in Pierce 2007)	3500	3500	21420	0
1998	Odell†		3000-6000	4500	27540	9180
1998	Schollnberger†		3300	3300	20196	0
1999	(Laherrere)	Consultant	2700	2700	16524	0
1999		(BP)		1860	11400	0
1999	Magoon^	USGS	2000	2000	12240	0
1999	(C. J. Campbell)		2000 (inc. polar and deepwater)	2000	12240	0
1999	(Duncan & Youngquist)		2042	2042	12497	0
2000		USGS^	2000-2300-2800 (5%-mean-95%)	2300	14076	918
2000		USGS[a]	3270	3270	20012	0
2000	Alhbrandt	USGS~	2250-3000-3850	3000	18360	2448
2000	(Salameh)	Consultant	2000	2000	12240	0
2000		US EIA^	3000	3000	18360	0
2000		IEA WEO 2000^	3345	3345	20471	0
2000	Bartlett^		2000-3000	2500	15300	3060
2000	(D. B. Reynolds)		350 (Gtons)	2400	14665	0
2001		EIA[c]	2248-3303-3896	3303	20214	2521
2001	Deffeyes^	Princeton University	1800–2100	1950	11934	918
2001	(Laherrere)		2050	2050	12546	0
2001		Shell†	4100 (all liquids)	4100	25092	0
2001		Shell†	3200-3800	3500	21420	1836

YEAR	AUTHOR	AFFILIATION	ULTIMATELY RECOVERABLE (Billion Barrels unless stated)	MEAN RECOVERABLE (Billion Barrels)	ULTIMATELY RECOVERABLE (EJ)	ERROR (EJ)
2002	(Bentley)		1700	1700	10404	0
2002		BGR [e]	2670	2670	16340	0
2002		USGS^	2200-3000-4000 (5%-mean-95%)	3000	18360	2448
2002	(Cavallo)		2300	2300	14076	0
2002	(Wood, Long, & Morehouse)	EIA	2250-3900	3075	18819	5049
2002	(Aleklett & Campbell)		1900	1900	11628	0
2002	(Korpela)		2200	2200	13464	0
2002		Shell (scenario)[f]	4000 (all liquids) 2900 conventional	2900	17748	0
2002	‘Nemesis'^		1950-2300	2125	13005	1071
2002	Smith^		2180	2180	13342	0
2002	Edwards†		3600	3600	22032	0
2003	Nehring (Andrews & Udall)		2500-3000	2750	16830	1530
2003	Laherrere [e]		3000 (all liquids)	3000	18360	0
2003		Energyfiles Ltd.[e]	2338 (all liquids)	2338	14309	0
2003		WETO Study [f]	3500 (all liquids)	3500	21420	0
2003	P-R Bauquis [e]		3000 (all liquids)	3000	18360	0
2003	(Bauquis)		2000-3000	2500	15300	3060
2004	(Wood, Long, & Morehouse)	EIA/USGS	2248-3003-3896	3003	18378	412
2004	(Hallock, Tharakan, Hall, Jefferson, & Wu)		1900-2900-4000	2900	17748	12852
2005	(Illum)		2510-2855	2683	16417	1056
2005	Deffeyes[c]		2013	2013	12320	0
2005		EIA[c]	3658	3658	22387	0
2005		Exxon[c]	3200	3200	19584	0

YEAR	AUTHOR	AFFILIATION	ULTIMATELY RECOVERABLE (Billion Barrels unless stated)	MEAN RECOVERABLE (Billion Barrels)	ULTIMATELY RECOVERABLE (EJ)	ERROR (EJ)
2005	Zagar & Campbell[c]		1850	1850	11322	0
2006	(Rempel, et al.)	BGR	392 (Gtonnes)	2680	16400	0
2007	Campbell	(ASPO)	2700	2700	16524	0
2007		(ASPO)	1850	1850	11322	0
2007		(ASPO) (All liquids)	2400-2700	2550	15606	0
2007	(Klett, Gautier, & Ahibrandt)	USGS	2248-3869	3059	18718	4960
2007	(Chu & Goldemberg)	InterAcademy Council	13268 (EJ)	2170	13280	0
2007		(WEC)		2270	13900	0
2007	(Robelius)		2250	2250	13770	0

† Estimates from (Pierce, 2007), ‡ Estimates from (MIT, 1977),
° Estimates from (Wolf Häfele, 1981), * Estimates from (Charles A.S. Hall, et al., 1986),
^ Estimate from (Bentley, 2002b), ~ Estimates from (Laherrere, 2001)
[a] Estimates from (Bauquis, 2003), [b] Estimate from (MacKenzie, 1998)
[c] Estimates from (Al-Husseini, 2006), [d] Estimates from (Costa Silva & Barata Alves, 2005)
[e] Estimates from (Meng & Bentley, 2008), [f] Estimates from (Bentley, Mannan, & Wheeler, 2007)
[g] Estimates from (Andrews & Udall, 2003), [h] Estimates from (Arthur, 1982),
[i] Estimates from (Michel Grenon, 1978)

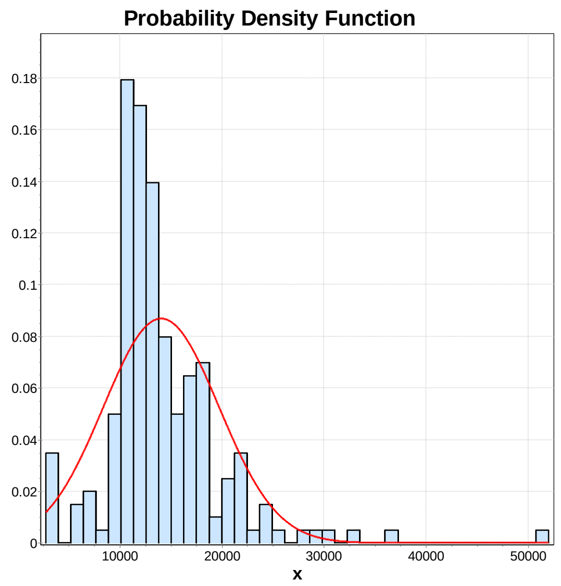


Figure C-3 Histogram of estimates of ultimately recoverable resources of conventional oil with normal and gamma distributions for comparison

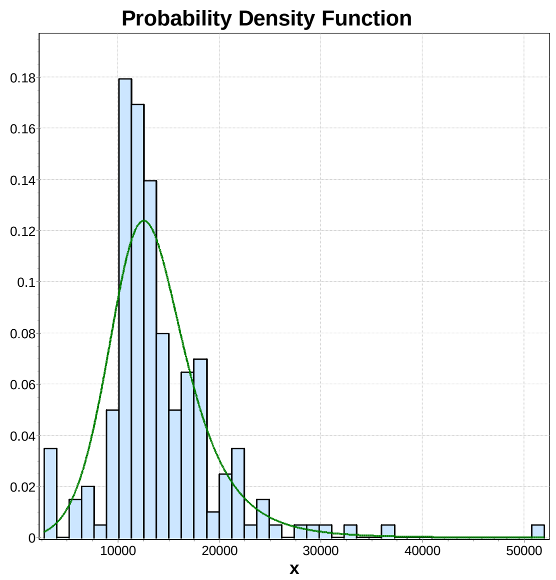


Figure C-4 Histogram of estimates of ultimately recoverable resources of conventional oil with log-logistic distribution for comparison

Table C-4

Table C-5 Goodness-of-fit statistics for normal and log-logistic distributions of estimates of ultimately recoverable resources of conventional oil

DISTRIBUTION		DEGREES OF FREEDOM	STATISTIC	P-VALUE
Normal	Kolmogorov-Smirnov	-	0.15477	1.1364E-4
	Anderson-Darling	-	7.1955	-
	Chi-Squared	7	65.349	1.2795E-11
Log-Logistic	Kolmogorov-Smirnov	-	0.10076	0.03142
	Anderson-Darling	-	1.8517	-
	Chi-Squared	7	16.095	0.02427

C.3 Unconventional Oil:

Table C-6 Estimates of the ultimately recoverable resources of unconventional oil

RESOURCE	YEAR	AUTHOR	AFFILIATION	MEAN RECOVERABLE (EJ)	ERROR (EJ)
Tar Sands	1974	(Thomas)		1836	0
Tar Sands	1977		(MIT)	1836	0
Tar Sands	1978		WEC Delphi Poll†	1361	419
Tar Sands	1978	(Ezra)		502	0
Tar Sands	1981	(Qadeer)		918	0
Tar Sands	1982	(Fraas)		1800	0
Tar Sands	1985	(J. Edmonds & Reilly)		3785	3060
Tar Sands	2002	(Bentley)		4896	0
Shale Oil	1978		WEC Delphi Poll†	1256	0
Shale Oil	1974	(Thomas)		9	0
Shale Oil	1982	(Fraas)		1100	0
Shale Oil	1982	Hafele		1893	0
Shale Oil	1978	(Ezra)		1214	0
Shale Oil	1985	(J. Edmonds & Reilly)		1163	0
Shale Oil	1977		(MIT)	734	0
Shale Oil	2002	(Bentley)		18360	0
Shale Oil	2007		(WEC)	17516	0
Shale Oil	1981	(Qadeer)		1	0
Shale Oil	1979	(Steele)		4086	0
NGL	1986		(WEC)	105	0
NGL	1974	(Thomas)		2020	0
NGL	2002	(Bentley)		1530	0
Heavy oil	1977		(MIT)	211	110
Heavy oil	2007		(WEC)	466	0
Deep Water Oil			(ASPO)	428	
All unconventional oil	1982	Hafele		13254	

† Estimates from (Michel Grenon, 1978)

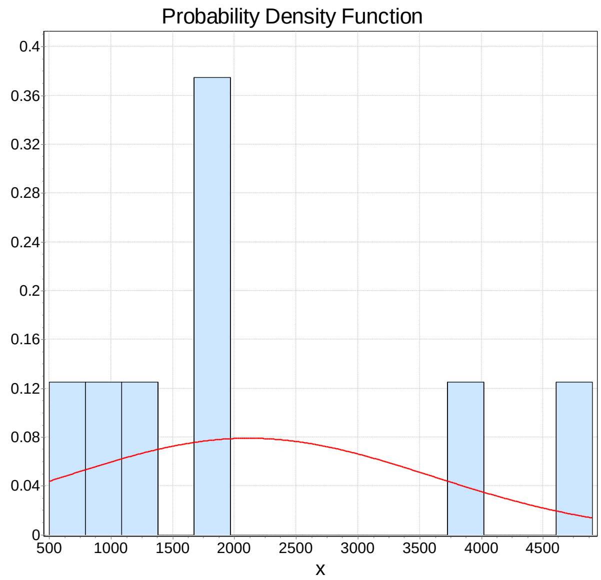


Figure C-5 Histogram of estimates of ultimately recoverable resources of tar sands with normal distribution for comparison

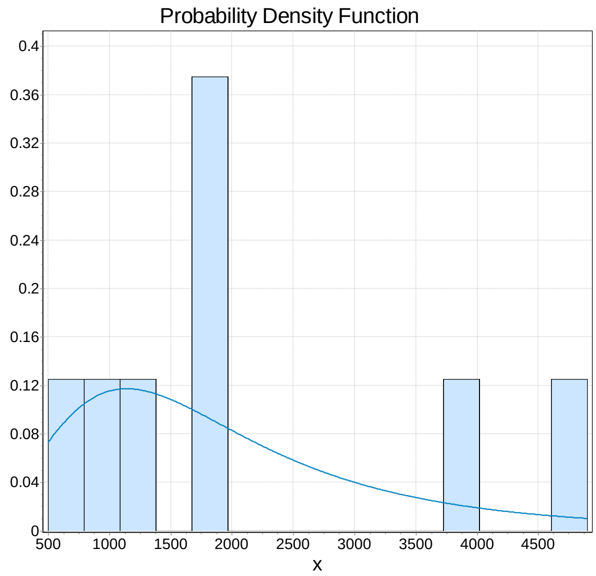


Figure C-6 Histogram of estimates of ultimately recoverable resources of tar sands with GEV distribution for comparison

Table C-7 Goodness-of-fit statistics for normal and GEV distributions of estimates of ultimately recoverable resources of tar sands

DISTRIBUTION		DEGREES OF FREEDOM	STATISTIC	P-VALUE
Normal	Kolmogorov-Smirnov	-	0.32511	0.29714
	Anderson-Darling	-	0.56451	-
	Chi-Squared	-	-	-
GEV	Kolmogorov-Smirnov	-	0.19925	0.85143
	Anderson-Darling	-	0.2778	-
	Chi-Squared			

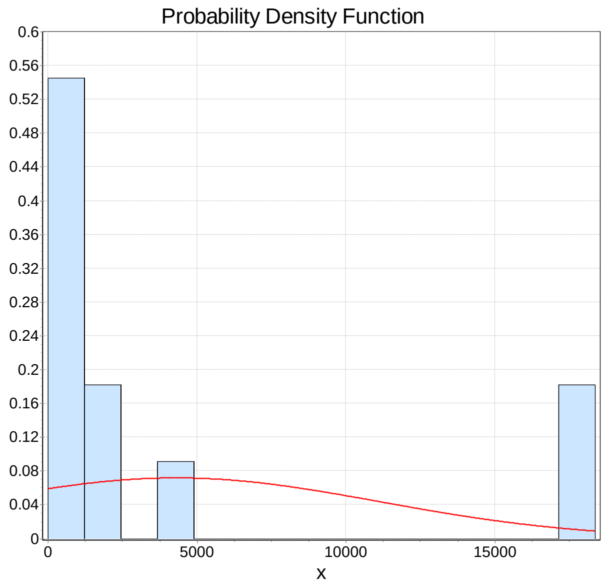


Figure C-7 Histogram of estimates of ultimately recoverable resources of shale oil with normal distribution for comparison

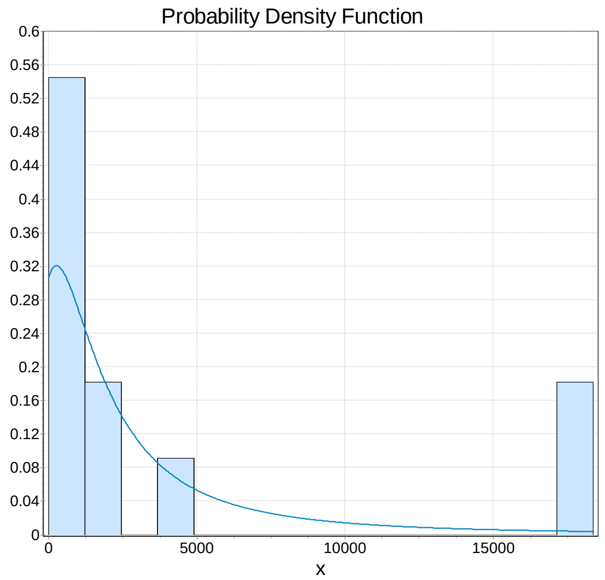


Figure C-8 Histogram of estimates of ultimately recoverable resources of shale oil with GEV distribution for comparison

Table C-8 Goodness-of-fit statistics for normal and GEV distributions of estimates of ultimately recoverable resources of shale oil

DISTRIBUTION		DEGREES OF FREEDOM	STATISTIC	P-VALUE
Normal	Kolmogorov-Smirnov	-	0.36514	0.08039
	Anderson-Darling	-	2.0126	-
	Chi-Squared	-	-	-
GEV	Kolmogorov-Smirnov	-	0.20206	0.68937
	Anderson-Darling	-	0.59311	-
	Chi-Squared	-	-	-

C.4 Conventional Gas:

Table C-9 Estimates of the ultimately recoverable resources of conventional gas

YEAR	AUTHOR	AFFILIATION	ULTIMATELY RECOVERABLE (Bboe) unless stated	ULTIMATELY RECOVERABLE (EJ)	ERROR (EJ)
1956	MacKinney†		650	3978	0
1956	-	US Dept. of Interior‡	860	5263	0
1958	Weeks†		860 – 1035	5795	536
1959	Weeks‡		1035	6334	0
1965	Weeks‡		1240	7589	0
1965	Hendricks†	USGS	2640	16157	0
1965	Weeks†		1250	7650	0
1965	MacKinney†		1250	7650	0
1967	Ryman†	ESSO	2070	12668	0
1967	-	Shell†	1760	10771	0
1968	MacKinney†		2000	12240	0
1968	Weeks†		1200	7344	0
1969	Hubbert†		1380 – 2070	10560	2110
1970		FPC*	2800	17136	0
1971	Weeks†		1240	7589	0
1973	Coppack‡		1300	7956	0
1973	Hubbert†		2070	12668	0
1973	Linden‡		1800	11016	0
1974	(Thomas)		1.1E+22 (Joules)	11000	0
1974	Hubbert*		2200	13464	0
1974	Parent & Linden†		1700	10404	0
1975	Kirkby & Adams†		900-1100	6304	612
1975	Moody & Geiger†		1400	8568	0
1975		National Academy of Science†	1230	7528	0
1976	Barthel†	BGR	1500	9180	0
1976	Grossling†		1900-4600	19890	8262
1977	(McMullen, et al.)		1E+22 (Joules)	10000	0
1977		American Gas Association*	1810	11077	0

YEAR	AUTHOR	AFFILIATION	ULTIMATELY RECOVERABLE (Bboe) unless stated	ULTIMATELY RECOVERABLE (EJ)	ERROR (EJ)
1977		MIT‡	1040-2080	9547	3180
1977		International Gas Union†	950	5814	0
1977	Parent & Linden		1700-1800	10710	306
1978	(Ezra)		1.84E+21 (Joules)	1840	0
1978		Dept Energy (in Ezra 1978)	7.16E+21 (Joules)	7160	0
1978	Despaires†		1400-1900	10098	1530
1978	McCormick†	American Gas Association	1750	10710	0
1979		(WEC)	1.05E+22 (Joules)	10500	0
1979		IGT*	1720-1790	10741	214
1979	Bois†		1500	9180	0
1979	Meyerhoff†		1350	8262	0
1979	Nehring†		800-1050	5661	765
1980	Parent & Linden†		1500-1700	9792	612
1980	Schubert†		1900	11628	0
1980		WEC†	1600	9792	0
1981		IIASA*	1700	10404	0
1982	Fraas		1.31E+22 (Joules)	13100	0
1982	Hafele		1.1E+22 (Joules)	11000	0
1984	Masters†		1400	8568	0
1986		(WEC)	3.34E+21 (Joules)	3340	0
1987	(Khan)		1.14E+22 (Joules)	11400	0
1991	Masters†		2800	17136	0
1992	(Nathwani, et al.)		1.05E+22 (Joules)	10500	0
1994	Masters†		2900	17748	0
1995	(R. Hill, et al.)		4.42E+21 (Joules)	4420	0
1995	Riva†		2000	12240	0
1998		(WEC)	6534 (EJ)	6534	0
1998	Schollnberger†		2300	14076	0
2000		USGS†	2560	15667	0
2001	(P. R. Odell)		391.8-497.8 (Gtoe)	18637	2221

YEAR	AUTHOR	AFFILIATION	ULTIMATELY RECOVERABLE (Bboe) unless stated	ULTIMATELY RECOVERABLE (EJ)	ERROR (EJ)
2001	(Laherrere)		10000 (trillion cubic feet)	10600	0
2001		CEDIGAZ†	2800-3500	19278	2142
2001	Deffeyes†		2000	12240	0
2001		Shell†	2300	14076	0
2001		Shell†	4700 (inc. unconventional)	28764	0
2002	(Bentley)		1400	8568	0
2002		BGR†	2800	17136	0
2003	Campbell	(ASPO)	1800	11016	0
2004	(Laherrere & Cutler)		2000	12240	0
2006	(Rempel, et al.)	BGR	426 (Gtoe)	17849	0
2007	(Chu & Goldemberg)	InterAcademy Council	10177 (EJ)	10177	0
2007		(WEC)	9.917E+21 (Joules)	9917	0

† Estimates from (Pierce, 2007), ‡ Estimates from (MIT, 1977),

*Estimates from (J. Edmonds & Reilly, 1985),

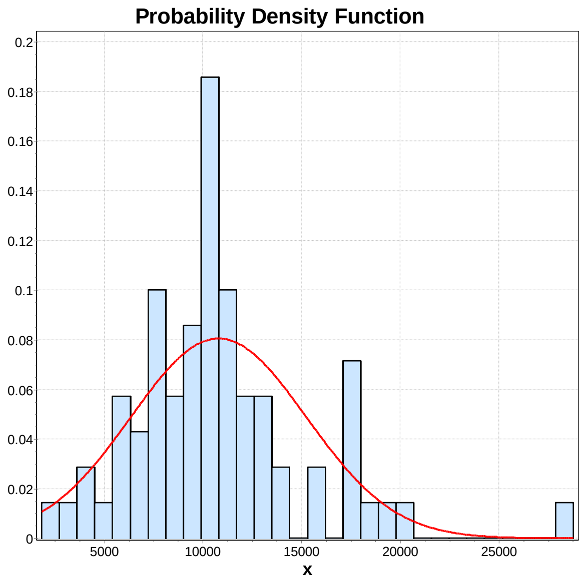


Figure C-9 Histogram of estimates of ultimately recoverable resources of conventional gas with normal distribution for comparison

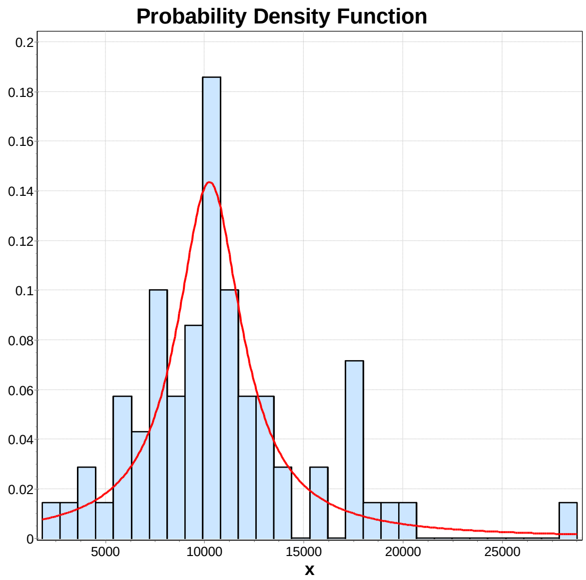


Figure C-10 Histogram of estimates of ultimately recoverable resources of conventional gas with cauchy distribution for comparison

Table C-10 Goodness-of-fit statistics for normal and cauchy distributions of estimates of ultimately recoverable resources of conventional gas

DISTRIBUTION		DEGREES OF FREEDOM	STATISTIC	P-VALUE
Normal	Kolmogorov-Smirnov	-	0.14641	0.08974
	Anderson-Darling	-	1.2805	-
	Chi-Squared	5	9.5928	0.08763
Cauchy	Kolmogorov-Smirnov	-	0.07487	0.79974
	Anderson-Darling	-	0.70461	-
	Chi-Squared	6	3.5852	0.7326

C.5 Unconventional Gas:

Table C-11 Estimates of the ultimately recoverable resources of unconventional gas

RESOURCE	YEAR	AUTHOR	AFFILIATION	ULTIMATELY RECOVERABLE (Billion barrels) unless stated	MEAN RECOVERABLE (EJ)	ERROR (EJ)
Tight Gas (coal seam)	1985	(J. Edmonds & Reilly)		370-860	3760	1500
Tight Gas (shale gas)	1986	(J. Edmonds & Reilly)		170-260	1320	280
Tight Gas	2002	(Bentley)		180	1100	0
Unconventional Gas	2001	(Laherrere)		2500 (Trillion cubic feet)	2650	0

C.6 Nuclear:

Table C-12 Estimates of the ultimately producible nuclear energy using burner reactors producing 173 TJ per tonne of U_3O_8

YEAR	AUTHOR	AFFILIATION	MEAN RECOVERABLE BURNER (EJ)	ERROR
1974	(Chandler)		2931	0
1974	(Thomas)		508	0
1977	(M Grenon)		872	0
1978	(Ezra)		2470	0
1979	(Cameron)		348	0
1982	Hafele	IIASA	379	0
1982	Hafele	IIASA	9467	0
1985	(J. Edmonds & Reilly)	IIASA	293	0
1995	(R. Hill, et al.)		353	0
2000		(WEA)	2042	0
2000		UNDP et al	554	0
2006	(Rempel, et al.)	Federal Institute for Geosciences and Natural Resources	1020	0
2006	(Rempel, et al.)	BGR	2963	0
2006	(Zittel & Schindler)	Energy Watch Group	1090	121
2007		(WEC)	781	0
2008		(EIA)	223	0

All estimates assume a deliverable energy content of uranium of 173 TJ per tonne

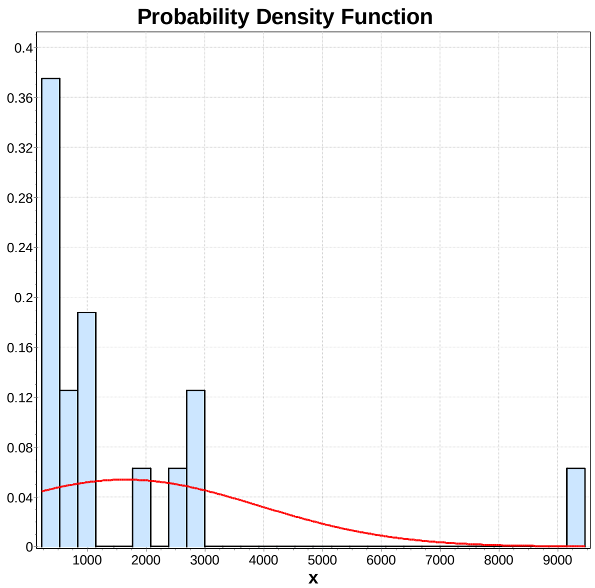


Figure C-11 Histogram of estimates of ultimately producible nuclear energy with normal distribution for comparison

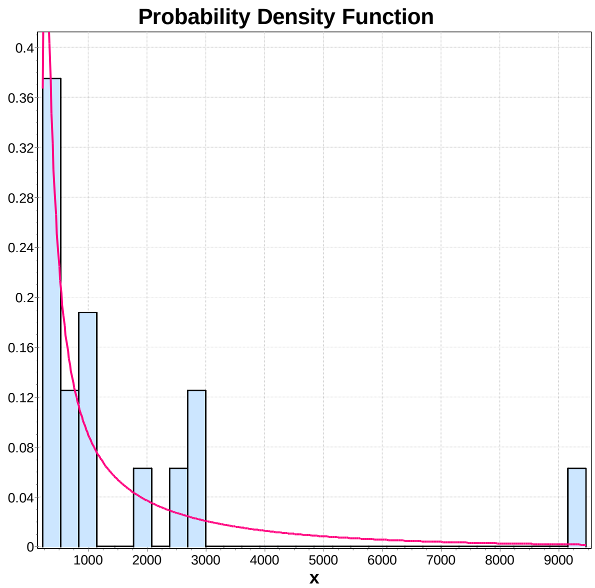


Figure C-12 Histogram of estimates of ultimately producible nuclear energy with fatigue life distribution for comparison

Table C-13 Goodness-of-fit statistics for normal and fatigue life distributions of estimates of ultimately recoverable resources of energy from uranium

DISTRIBUTION		DEGREES OF FREEDOM	STATISTIC	P-VALUE
Normal	Kolmogorov-Smirnov	-	0.28293	0.12606
	Anderson-Darling	-	2.1369	-
	Chi-Squared	1	4.931	0.02638
Fatigue Life	Kolmogorov-Smirnov	-	0.09761	0.99407
	Anderson-Darling	-	0.18469	-
	Chi-Squared	1	0.0762	0.78252

C.7 Biomass:

Table C-14 Estimates of technical potential of biomass

YEAR	AUTHOR	AFFILIATION	ULTIMATE POTENTIAL (EJ/yr)	ERROR
1979	(Wolf Häfele)		189	
1979	(Wolf Häfele)		164	
1981	(Wolf Häfele)	IIASA	189	0
1981	(Wolf Häfele)	IIASA	66	0
1985	(J. Edmonds & Reilly)		1905	0
1990	(Lashof & Tirpak)		345	116
1992	(Starr, et al.)		105	0
1993	(D. O. Hall, Rosillo-Calle, Williams, & Woods)		112	0
1993	(T. B. J. Johansson, Kelly, Reddy, & Williams)		78	0
1993	(D. O. Hall, et al.)		180	0
1993	(T. B. J. Johansson, Kelly, Reddy, & Williams)		86	0
1993	(Lazarus, et al.)	Stockholm Environmental Institute	146	92
1994	(Nitsch)		71	
1995	(R. Hill, et al.)		29	0
1995	(Williams)	IPCC	46	0
1995	(Williams)	Pacific Northwest Laboratories	154	0
1995	(Gilland)		144	10
1996	(J. A. Edmonds, Wise, Sands, Brown, & Kheshgi)	Pacific Northwest National Laboratory	100	0
1996	(Leemans, van Amstel, Battjes, Kreileman, & Toet)		153	0
1997	(B. Johansson)		1300	
1998	(Nakicenovic, Grübler, & McDonald, 1998)	WEC/IIASA	220	46
1998	(Nakicenovic, et al., 1998)	WEC/IIASA	250	133
1999	Yamamoto†		272	0
1999	Sorensen†	Roskilde University	41	0

YEAR	AUTHOR	AFFILIATION	ULTIMATE POTENTIAL (EJ/yr)	ERROR
2000	(Nakicenovic & Swart)	IPCC	222	155
2001	(Fischer & Schrattenholzer)	IIASA	231	0
2001		(IPCC)	440	0
2001	Fischer & Schrattenholzer†		133	22
2001	Fischer & Schrattenholzer†		410	40
2002	(J. R. Moreira)		1301	0
2002	(Lightfoot & Green)		268	0
2003	(Gross, Leach, & Bauen)		59	31
2003	(Berndes, Hoogwijk, & van den Broek)		243	208
2004	(M. M. Hoogwijk)		584	551
2004	(Thomas B Johansson, McCormick, Neij, & Turkenburg)		250	0
2005	(M. Hoogwijk, Faaij, Eickhout, de Vries, & Turkenburg)		755	360
2005	(Schock)		250	0
2006	(Berndes)		108	27
2006	(van Sark, Patel, Faaij, & Hoogwijk)		570	430
2006	(Obersteiner et al.)		2225	975
2006	(J. X. C. Moreira)		1643	0
2007	(Peter & Lehmann)	Energy Watch Group	641	0
2007		(WEC)	2	0
2007	(de Vries, van Vuuren, & Hoogwijk)		171	99
2008	(Field, Campbell, & Lobell)		27	0
2008	(MacKay) (assuming all cropland for energy		284	0

† Estimates from (Berndes, et al., 2003)

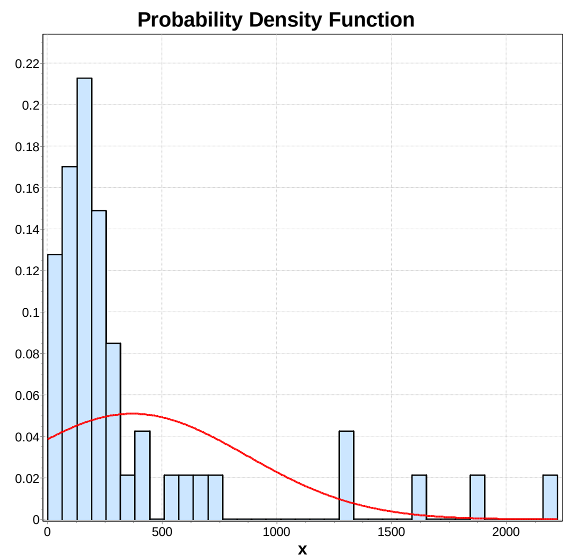


Figure C-13 Histogram of estimates of technical potential of biomass with normal distribution for comparison

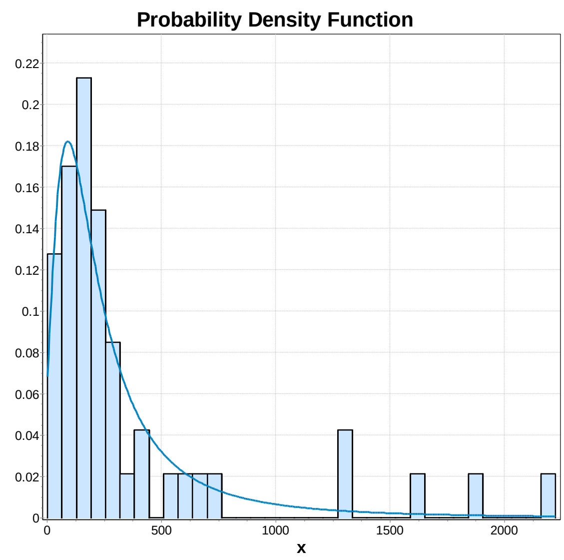


Figure C-14 Histogram of estimates of technical potential of biomass with GEV distribution for comparison

Table C-15 Goodness-of-fit statistics for normal and GEV distributions to estimates of technical potential of biomass

DISTRIBUTION		DEGREES OF FREEDOM	STATISTIC	P-VALUE
Normal	Kolmogorov-Smirnov	-	0.3143	1.2631E-4
	Anderson-Darling	-	6.3572	-
	Chi-Squared	3	12.215	0.00668
GEV	Kolmogorov-Smirnov	-	0.10854	0.59866
	Anderson-Darling	-	0.34554	-
	Chi-Squared	4	2.8383	0.58525

C.8 Hydro:

Table C-16 Estimates of technical potential of hydro

YEAR	AUTHOR	AFFILIATION	ULTIMATE POTENTIAL (EJ/yr)	ERROR (EJ/yr)
1974	(Chandler)		105	0
1978		WEC Delphi Poll (Michel Grenon)	35	0
1978	(C. W. I. Bullard)		175	0
1979	(Wolf Häfele)		91	0
1982	Hafele	IIASA	95	0
1982	Hafele	IIASA	47	0
1985	(J. Edmonds & Reilly)		37	0
1988	(Goldemberg, Johansson, Reddy, & Williams)		63	0
1992	(Starr, et al.)		30	0
1992	(Jackson)		23	3
1994	(Nitsch, 1994)		36	0
1995	(R. Hill, et al.)		69	0
1995		(WEC)	32	0
1995	(Gilland)		43	0
1997	(B. Johansson)		130	0
1998		(ICOLD)	52	0
1998	World Atlas (in Nitsch 1999)		47	0
2000		(WEA)	125	0
2002	(Horlacher)		52	0
2004	(Bhatti, Bansal, & Kothon)		49	4
2004	(Thomas B Johansson, et al.)		50	0
2005	(Schock)		60	0

YEAR	AUTHOR	AFFILIATION	ULTIMATE POTENTIAL (EJ/yr)	ERROR (EJ/yr)
2006		(IEA)	123	0
2006	(Tsao, Lewis, & Crabtree)		16	0
2007		(WEC)	144	0
2007		(IEA)	6	0
2007	(Chu & Goldemberg)	InterAcademy Council	50	0
2007	(Bakis)		52	0
2008	(MacKay)	International Hydropower Association	123	0
2008	(Zerta, et al.)		51	0
2009		(UN)	150	0

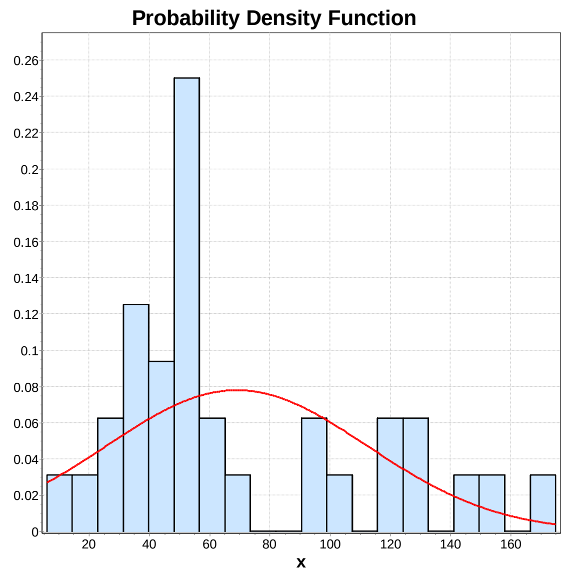


Figure C-15 Histogram of estimates of technical potential of hydro with normal distribution for comparison

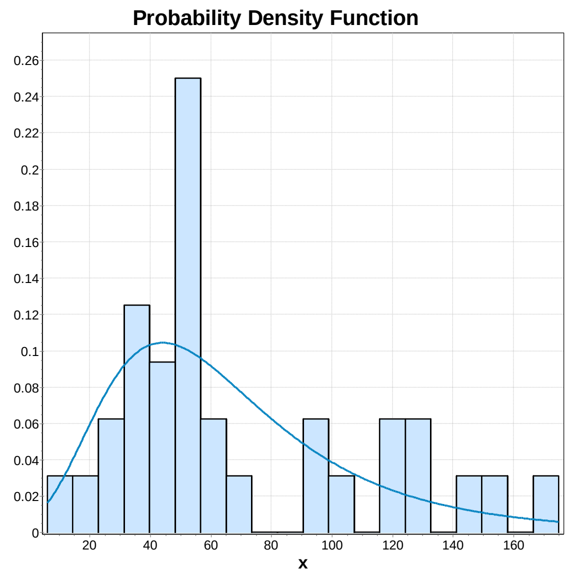


Figure C-16 Histogram of estimates of technical potential of hydro with general extreme value (GEV) distribution for comparison

Table C-17 Goodness-of-fit statistics for normal and GEV distributions to estimates of technical potential of hydro

DISTRIBUTION		DEGREES OF FREEDOM	STATISTIC	P-VALUE
Normal	Kolmogorov-Smirnov	-	0.24733	0.03284
	Anderson-Darling	-	1.6202	-
	Chi-Squared	3	11.168	0.01085
GEV	Kolmogorov-Smirnov	-	0.17208	0.26746
	Anderson-Darling	-	0.67572	-
	Chi-Squared	3	5.4785	0.13993

C.9 Geothermal:

Table C-18 Estimates of total technical potential of geothermal

YEAR	AUTHOR	AFFILIATION	ULTIMATE POTENTIAL (EJ/yr)	ERROR (EJ/yr)
1974	(Chandler)		4	0
1979	(Wolf Häfele)		11	0
1982	Hafele	IIASA	11	0
1994	(Nitsch)		21	0
1997	(B. Johansson)		20	0
1999	Gawell†		2	1
2000		(WEA)	5000	0
2000	Stefansson (low heat)†		1800	0
2001	(Ingvar B. Fridleifsson)		1400	0
2003	(Gross, et al., 2003)		79	65
2003	(Vaclav Smil, 2003)		1	0
2004	(Graßl, et al.)	German Advisory Council on Global Change	30	0
2004	(Thomas B Johansson, et al.)		5000	0
2004	(Dickson & Fanelli)		82	0
2005	(Schock)		5000	0
2006	(Tsao, et al.)		36	0
2007	(Peter & Lehmann)	Energy Watch Group (direct use)	1400	0
2008	(MacKay)		63	0
2008	(Zerta, et al.)		50	0
2008	(I.B. Fridleifsson et al.) (low heat)	IPCC	142	0

† Estimates from (Bertani, 2003)

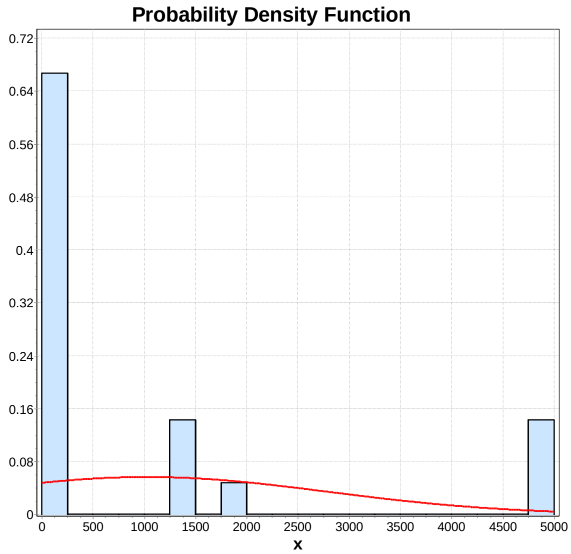


Figure C-17 Histogram of estimates of technical potential of geothermal with normal distribution for comparison

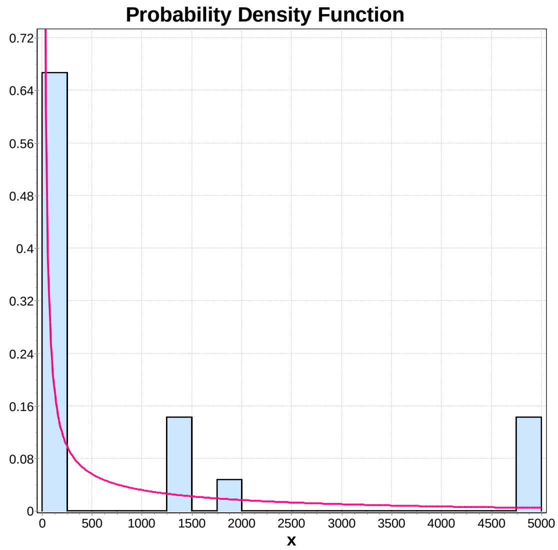


Figure C-18 Histogram of estimates of technical potential of geothermal with fatigue life distribution for comparison

Table C-19 Goodness-of-fit statistics for normal and fatigue life distributions to estimates of technical potential of geothermal

DISTRIBUTION		DEGREES OF FREEDOM	STATISTIC	P-VALUE
Normal	Kolmogorov-Smirnov	-	0.35886	0.00629
	Anderson-Darling	-	3.544	-
	Chi-Squared	1	5.1637	0.02306
Fatigue Life	Kolmogorov-Smirnov	-	0.14241	0.73613
	Anderson-Darling	-	0.44465	-
	Chi-Squared	2	1.5832	0.45312

Table C-20 Estimates of technical potential of geothermal for the production of electricity

YEAR	AUTHOR	AFFILIATION	ULTIMATE POTENTIAL (EJ/yr)	ERROR (EJ/yr)
1998	Bjornsson†		43	0
2000	Stefansson†		81	0
2001	(Ingvar B. Fridleifsson)		40	5
2004	(Dickson & Fanelli)		81	0
2007	(Peter & Lehmann)	Energy Watch Group (electricity)	81	0
2008	(I.B. Fridleifsson, et al.)	IPCC	2	0

† Estimates from (Bertani, 2003)

C.10 Wind:

Table C-21 Estimates of technical potential of wind

YEAR	AUTHOR	AFFILIATION	ULTIMATE POTENTIAL (EJ/yr)	ERROR
1963	(Brooks & Miller)		6120	0
1979	(Wolf Häfele)		95	0
1981	(Wolf Häfele)	IIASA	95	0
1988	(Goldemberg, et al.)		95	0
1992	(Jackson)		54	0
1993	(Grubb & Meyer)		32	0
1994	(Nitsch)		36	0
1997	(B. Johansson)		130	0
1999	Wind†		191	0
2000		(WEA)	436	409
2001	(Leutz, Ackermann, Suzuki, Akisawa, & Kashiwagi)		133	0
2002	(Gross, et al.)		108	36
2004	(M. Hoogwijk, et al.)		346	0
2004	(Graßl, et al.)	German Advisory Council on Global Change	140	0
2004	(M. M. Hoogwijk)		346	0
2004	(Thomas B Johansson, et al.)		600	0
2005	(Archer & Jacobson)		386	0
2005	(Schock)		600	0
2006	(van Sark, et al.)		345	0
2006	(de Vries, et al.)		185	103
2006	(Tsao, et al.)		75	0
2007	(Peter & Lehmann)	Energy Watch Group	343	36
2008	(Jacobson)	Stanford	407	0
2008	(MacKay)	European Wind Energy Association	19	0
2008	(Zerta, et al.)		216	0

† Estimates from (Nitsch, 1994)

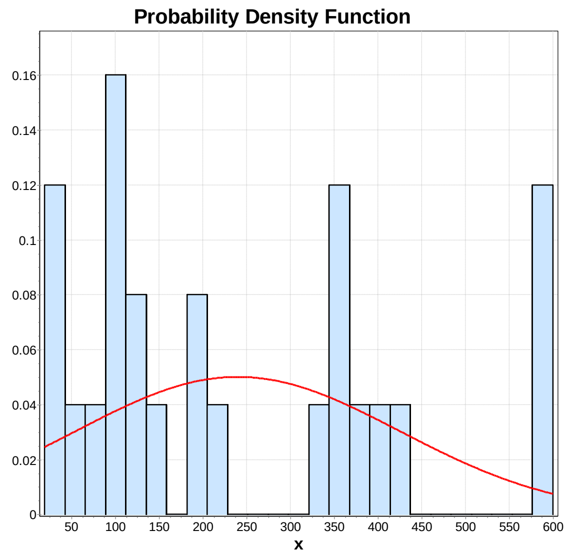


Figure C-19 Histogram of estimates of technical potential of wind with normal distribution for comparison

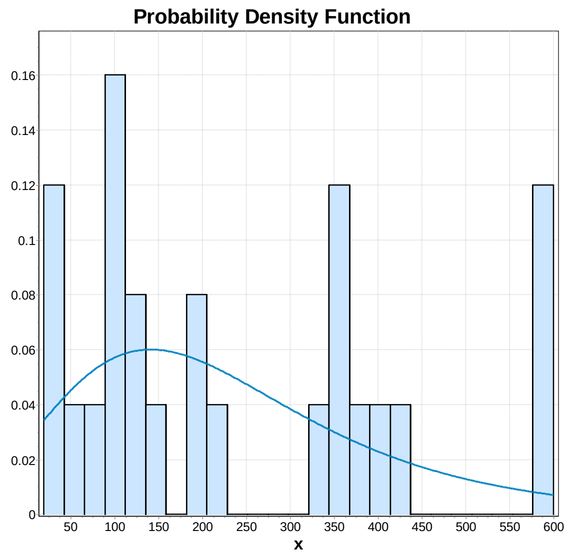


Figure C-20 Histogram of estimates of technical potential of wind with general extreme value (GEV) distribution for comparison

Table C-22 Goodness-of-fit statistics for normal and GEV distributions to estimates of technical potential of wind

DISTRIBUTION		DEGREES OF FREEDOM	STATISTIC	P-VALUE
Normal	Kolmogorov-Smirnov	-	0.18082	0.64645
	Anderson-Darling	-	0.49087	-
	Chi-Squared	1	1.5555	0.21233
GEV	Kolmogorov-Smirnov	-	0.14162	0.88404
	Anderson-Darling	-	0.34446	-
	Chi-Squared	1	0.07201	0.78843

C.11 Solar:

Table C-23 Estimates of technical potential of solar thermal

YEAR	AUTHOR	AFFILIATION	ULTIMATE POTENTIAL (EJ/yr)	ERROR
1979	(Wolf Häfele)		11	0
1981	(Wolf Häfele)	IIASA	186	0
2006	(Tsao, et al.)		12362	0
2007	(Peter & Lehmann)	Energy Watch Group	186	0
2008	(Zerta, et al.)		230	0

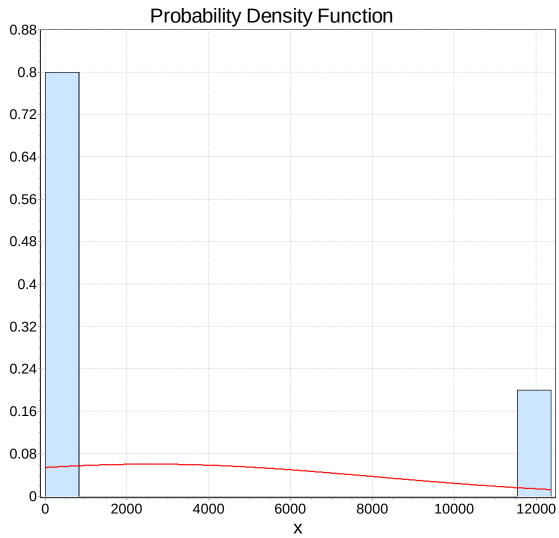


Figure C-21 Histogram of estimates of technical potential of solar thermal with normal distribution for comparison

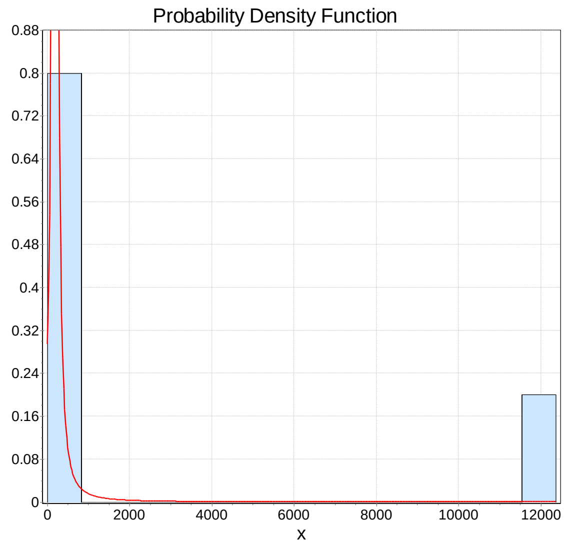


Figure C-22 Histogram of estimates of technical potential of solar thermal with cauchy distribution for comparison

Table C-24 Goodness-of-fit statistics for normal and cauchy distributions to estimates of technical potential of solar thermal

DISTRIBUTION		DEGREES OF FREEDOM	STATISTIC	P-VALUE
Normal	Kolmogorov-Smirnov	-	0.46753	0.16158
	Anderson-Darling	-	1.1657	-
	Chi-Squared	-	-	-
Lognormal	Kolmogorov-Smirnov	-	0.25146	0.84005
	Anderson-Darling	-	0.99638	-
	Chi-Squared	-	-	-

Table C-25 Estimates of technical potential of PV

YEAR	AUTHOR	AFFILIATION	ULTIMATE POTENTIAL (EJ/yr)	ERROR
2004	(M. M. Hoogwijk)		1318	0
2006	(van Sark, et al.)		1340	0
2006	(Tsao, et al.)		23652	0
2007	(Peter & Lehmann)	Energy Watch Group	43	0
2007	(de Vries, et al.)		2709	0
2008	(Zerta, et al.)		94	0

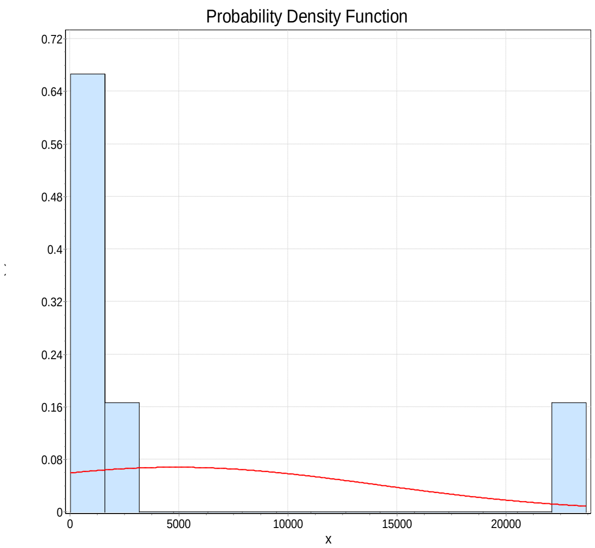


Figure C-23 Histogram of estimates of technical potential of PV with normal distribution for comparison

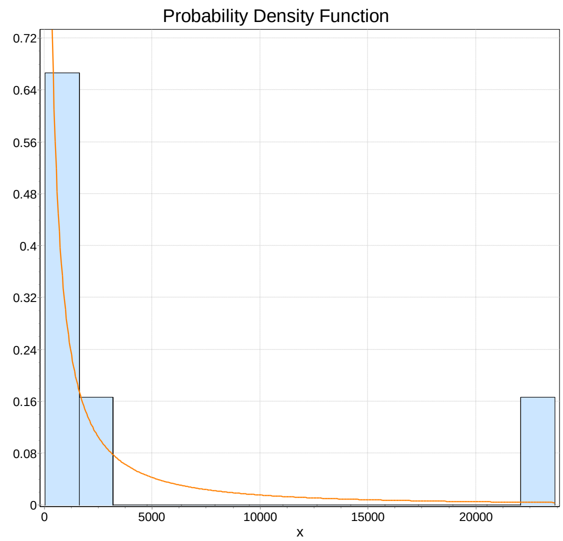


Figure C-24 Histogram of estimates of technical potential of PV with Lognormal distribution for comparison

Table C-26

Table C-27 Goodness-of-fit statistics for normal and lognormal distributions to estimates of technical potential of PV

DISTRIBUTION		DEGREES OF FREEDOM	STATISTIC	P-VALUE
Normal	Kolmogorov-Smirnov	-	0.42516	0.16896
	Anderson-Darling	-	1.2409	-
	Chi-Squared	-	-	-
Lognormal	Kolmogorov-Smirnov	-	0.24328	0.79623
	Anderson-Darling	-	0.31508	-
	Chi-Squared	-	-	-

Table C-28 Estimates of technical potential of STEC

YEAR	AUTHOR	AFFILIATION	ULTIMATE POTENTIAL (EJ/yr)	ERROR
2007	(Peter & Lehmann)	Energy Watch Group	55	0

Table C-29
Table C-30 Estimates of technical potential of all solar

YEAR	AUTHOR	AFFILIATION	ULTIMATE POTENTIAL (EJ/yr)	ERROR
1963	(Brooks & Miller)		86400	0
1992	(Starr, et al.)		57	0
1994	(Nitsch)		888	0
1995	(Gilland)		85	0
1997	(B. Johansson)		2600	0
1999		IIASA / WEC (Andersson & Jacobsson, 2000)	515	200
2000		(WEA)	25706	24131
2002	(Gross, et al.)		94	50
2004	(Graßl, et al.)	German Advisory Council on Global Change	1000	0
2004	(Thomas B Johansson, et al.)		1600	0.2
2005	(Schock)		1600	0

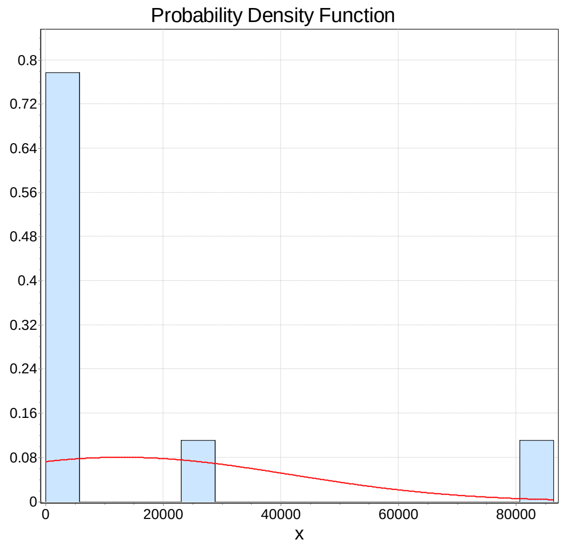


Figure C-25 Histogram of estimates of technical potential of all solar with normal distribution for comparison

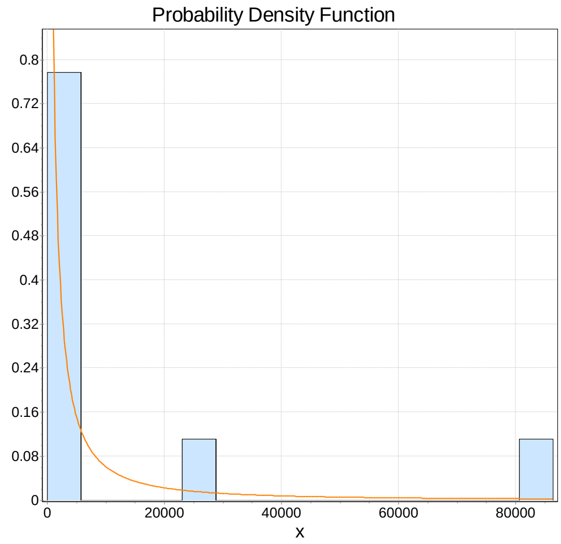


Figure C-26 Histogram of estimates of technical potential of all solar with lognormal distribution for comparison

Table C-31 Goodness-of-fit statistics for normal and lognormal distributions to estimates of technical potential of all solar energy

DISTRIBUTION		DEGREES OF FREEDOM	STATISTIC	P-VALUE
Normal	Kolmogorov-Smirnov	-	0.41598	0.05969
	Anderson-Darling	-	1.9487	-
	Chi-Squared	-	-	-
Lognormal	Kolmogorov-Smirnov	-	0.17358	0.90848
	Anderson-Darling	-	0.36806	-
	Chi-Squared	-	-	-

C.12 Ocean:

Table C-32 Estimates of technical potential of all ocean, OTEC, wave and tidal energy[3]

YEAR	AUTHOR	AFFILIATION	ULTIMATE POTENTIAL (EJ/yr)	ERROR
1994	(Nitsch)		7	0
1997	(B. Johansson, 1997)		20	0
2005	(Schock)		10	0
2006	(Tsao, et al.)		1	0
1979	(Wolf Häfele)		32	0
1981	(Wolf Häfele)	IIASA	32	0
2000	(Fetter)		100	0
2006	(Tsao, et al.)		1	0
1981	(Wolf Häfele)	IIASA	1	0
1986		(WEC)	1	0
1992	(Jackson)		4	1
2000		(WEA)	65	0
2002	(Gross, et al.)		11	4
2003	(Barstow, Mørk, Mollison, & Cruz)		3	2
2006	(Tsao, et al.)		3	0
2007		(WEC)	2	1
2008	(Jacobson)	Stanford	8	5
2008	(MacKay)		4	0
1974	(Chandler)		2	0
1977	(McMullen, et al.)		1	0
1979	(Wolf Häfele)		1	0
1981	(Wolf Häfele)	IIASA	1	0
1986		(WEC)	1	0
1992	(Jackson)		1	0
1993	(Hammons)		3	1
1994	(Nitsch, 1994)		7	0
2002	(Gross, et al.)		13	0
2003	(Vaclav Smil)		5	0
2004	(Kowalik)		2	1
2005	(Schock)		10	0
2006	(Tsao, et al.)		1	0

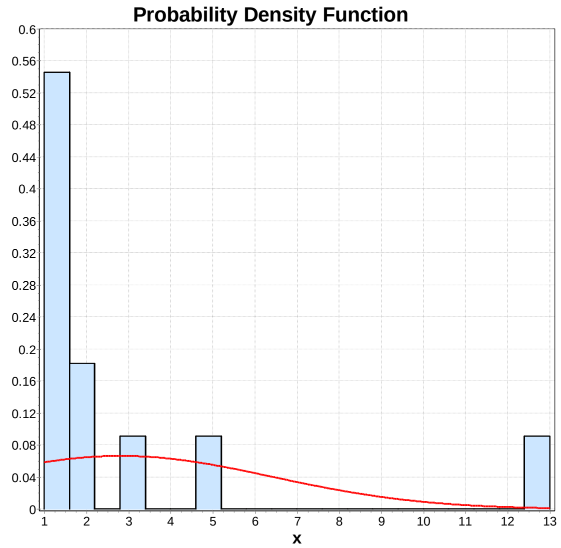


Figure C-27 Histogram of estimates of technical potential of tidal energy with normal distribution for comparison

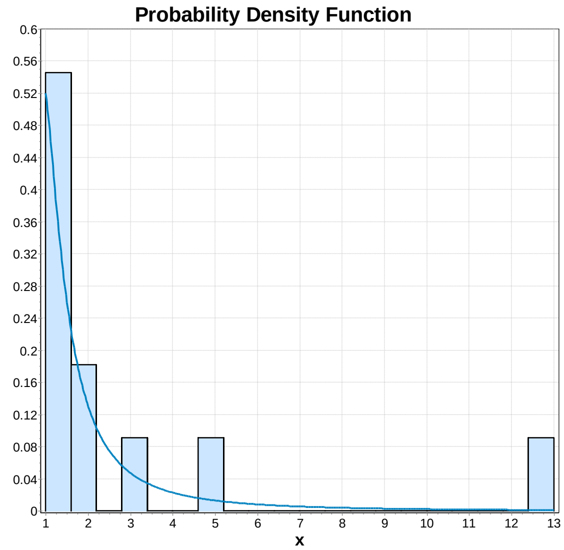


Figure C-28 Histogram of estimates of technical potential of tidal energy with GEV distribution for comparison

Table C-33 Goodness-of-fit statistics for normal and GEV distributions to estimates of technical potential of tidal energy

DISTRIBUTION		DEGREES OF FREEDOM	STATISTIC	P-VALUE
Normal	Kolmogorov-Smirnov	-	0.31715	0.17528
	Anderson-Darling	-	1.9042	-
	Chi-Squared	-	-	-
GEV	Kolmogorov-Smirnov	-	0.31564	0.17931
	Anderson-Darling	-	1.1004	-
	Chi-Squared	1	0.73974	0.38974

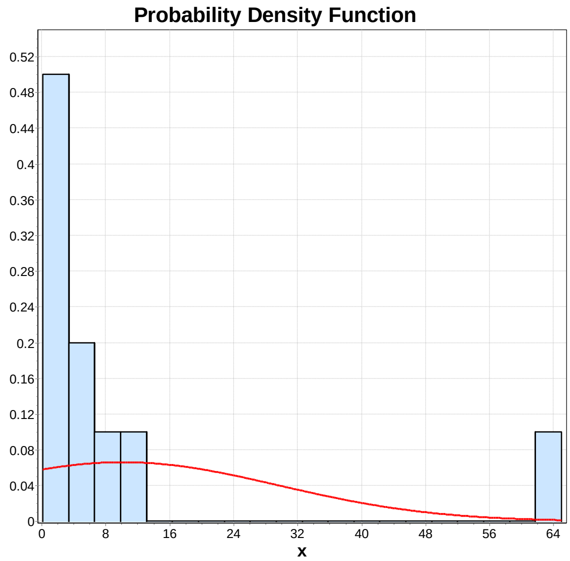


Figure C-29 Histogram of estimates of technical potential of wave energy with normal distribution for comparison

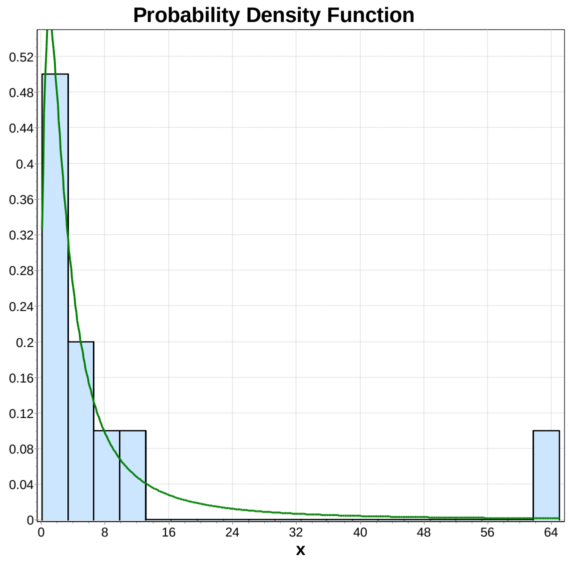


Figure C-30 Histogram of estimates of technical potential of wave energy with frechet distribution for comparison

Table C-34 Goodness-of-fit statistics for normal and frechet distributions to estimates of technical potential of wave energy

DISTRIBUTION		DEGREES OF FREEDOM	STATISTIC	P-VALUE
Normal	Kolmogorov-Smirnov	-	0.38197	0.08039
	Anderson-Darling	-	2.1967	-
	Chi-Squared	-	-	-
Frechet	Kolmogorov-Smirnov	-	0.15937	0.92777
	Anderson-Darling	-	0.2321	-
	Chi-Squared	1	4.1685E-4	0.99485

APPENDIX D. FORECASTING BASED ON GROWTH CYCLES

D.1 Forecasting using linearisation technique

Using this linearization technique we may now determine the values of r and K which best fit the historical production data using a residual sum of squares (R^2) method.

D.1.1 Coal:

As can be seen the linearization technique for actual historic data (see Figure D-1) does not give us nice straight line. Instead we find several periods where the data seems to indicate logistic growth. Unfortunately as cumulative production progresses the value of the horizontal intercept K, representative of the ultimately recoverable reserves, increases, such that this technique seems only to offer a lower bound to the value K. The line of best fit for the period 1938-2007 crosses the horizontal axis at a value of 53400 EJ. The main problem with the method is that the value of K is sensitive to the rate of production describing a zigzag curve rather than a straight line.

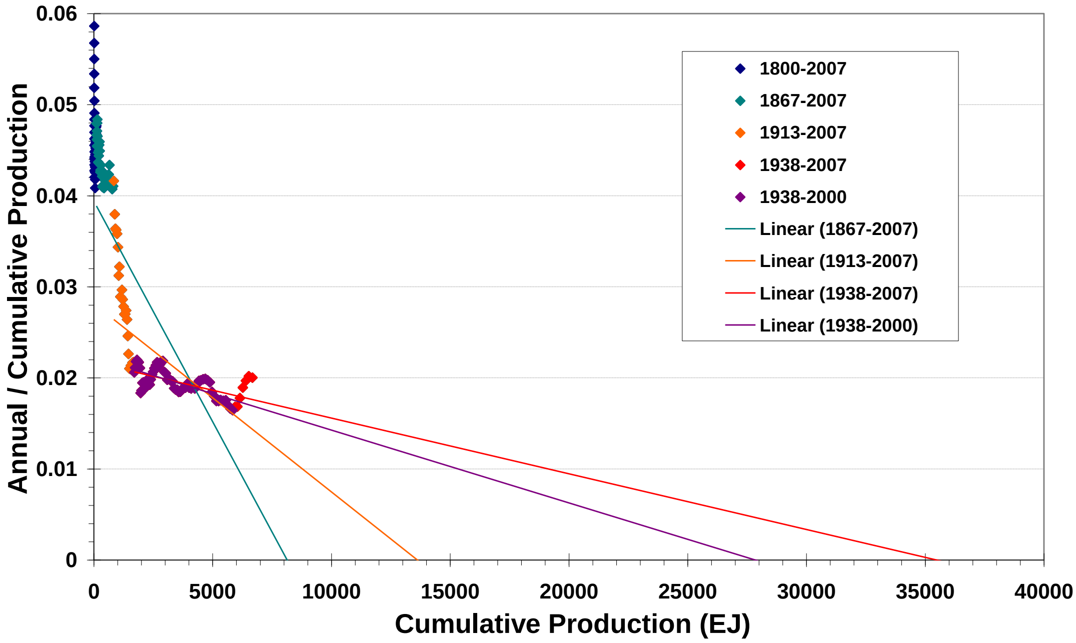


Figure D-1 Linearisation method applied to coal production data of various historic periods

If we now use these values for r and K to plot the rate of change of the logistic growth curve and compare this with historic data for annual coal production (see Figure D-2) we can see that the curve for the periods 1867-2007 predicts that coal production should already have peaked in 1990. The curve for the period 1913-2007 predicts a peak in production in 2010 at a rate of production, 95 EJ per year, which has already been surpassed. The curves for the periods 1938-2000 and 1938-2007 predict peaks in production in 2083 and 2102 at rates of 205 and 274 EJ per year, respectively but, still lower than the IEA estimates for coal production to 2030 (IEA, 2008c).

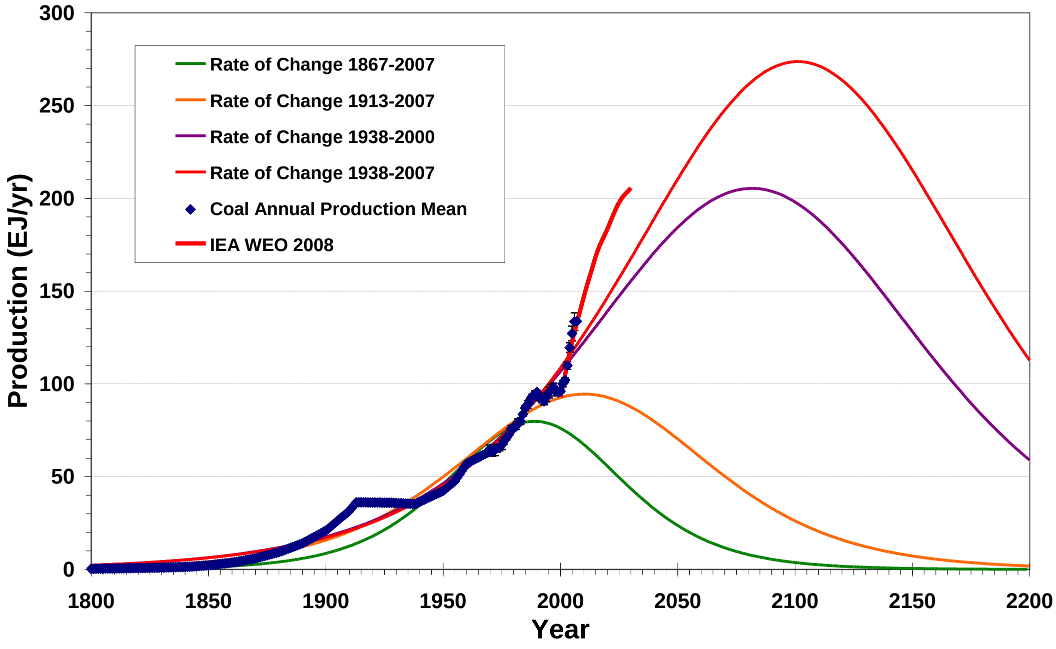


Figure D-2 Annual coal production compared with rate of change of logistic growth curves for various values of r and K

D.1.2 Oil:

The data for oil production (see Figure D-3) seems to fit the linearisation technique slightly better with distinct periods of, somewhat, stable activity between 1965-1985 and 1965-2007. Again the value of K increases with cumulative production.

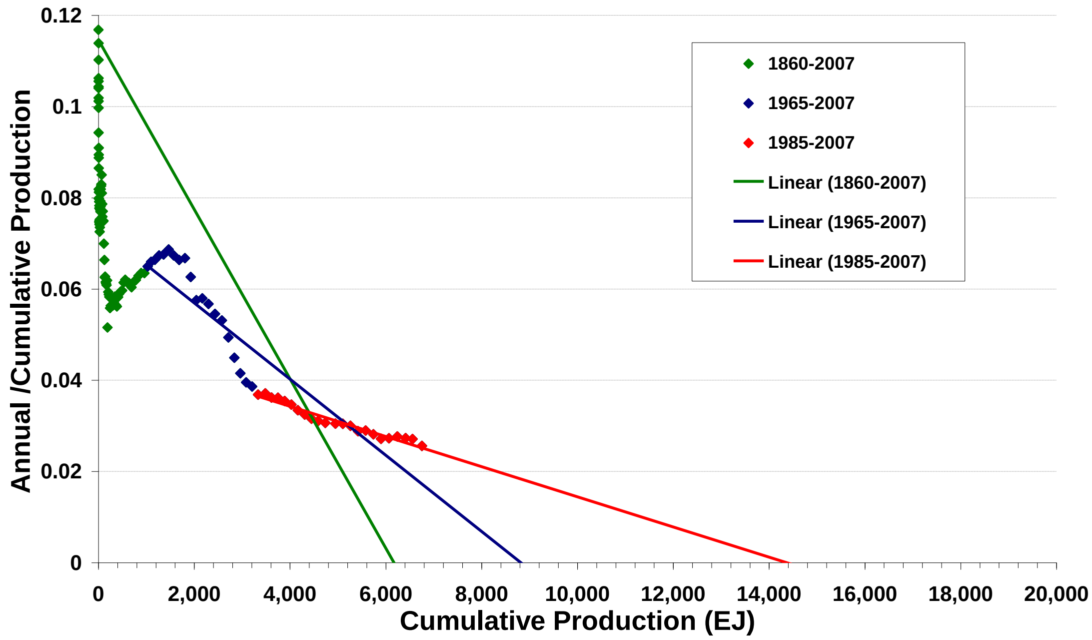


Figure D-3 Linearisation of conventional oil production for various periods

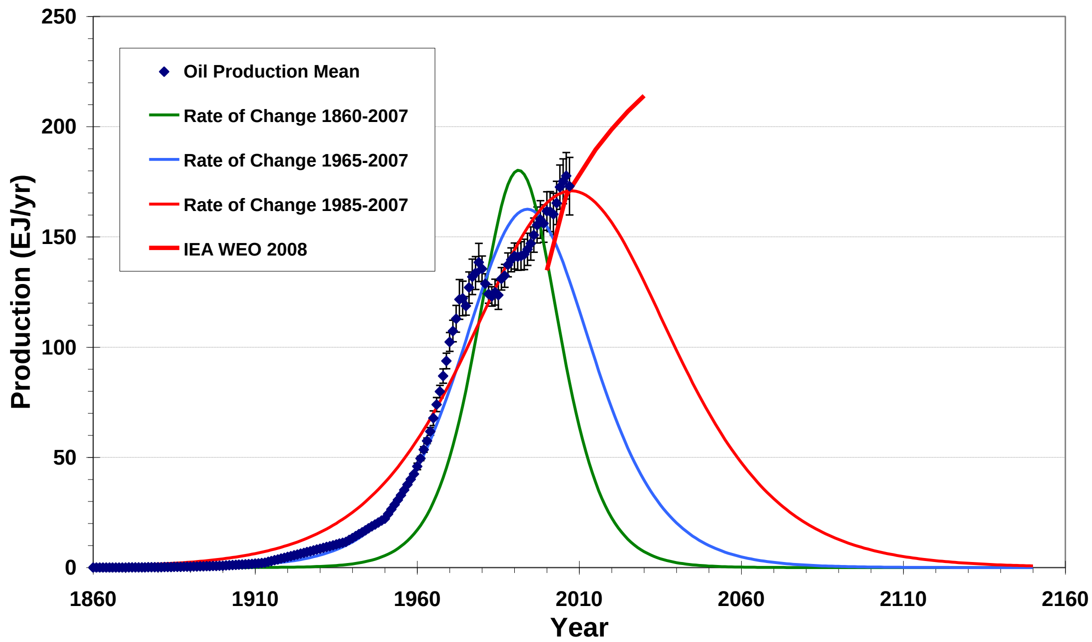


Figure D-4 Annual oil production compared with rate of change of logistic growth curves for various values of r and K

Plotting the rate of change of the logistic curve for the various values of r and K and comparing with annual oil production (see Figure D-4) we see that the curves for the periods 1860-2007 and 1965-2007 predict that oil production would have peaked in 1992 and 1995, at rates of 180 and 162 EJ per year respectively. The curve for the period 1985-2007 predicts a peak in 2008 at 171 EJ per year, again considerably lower than IEA projections out to 2030 (IEA, 2008c).

D.1.3 Gas:

The linearisation curve for gas production (see Figure D-5) has a very similar shape to that for oil production (see Figure D-6**Error! Reference source not found.**). Again we see periods of relative stability in the slope of the curve between 1970-1990 and 1990-2007. Again, the value of K increases as cumulative production increases

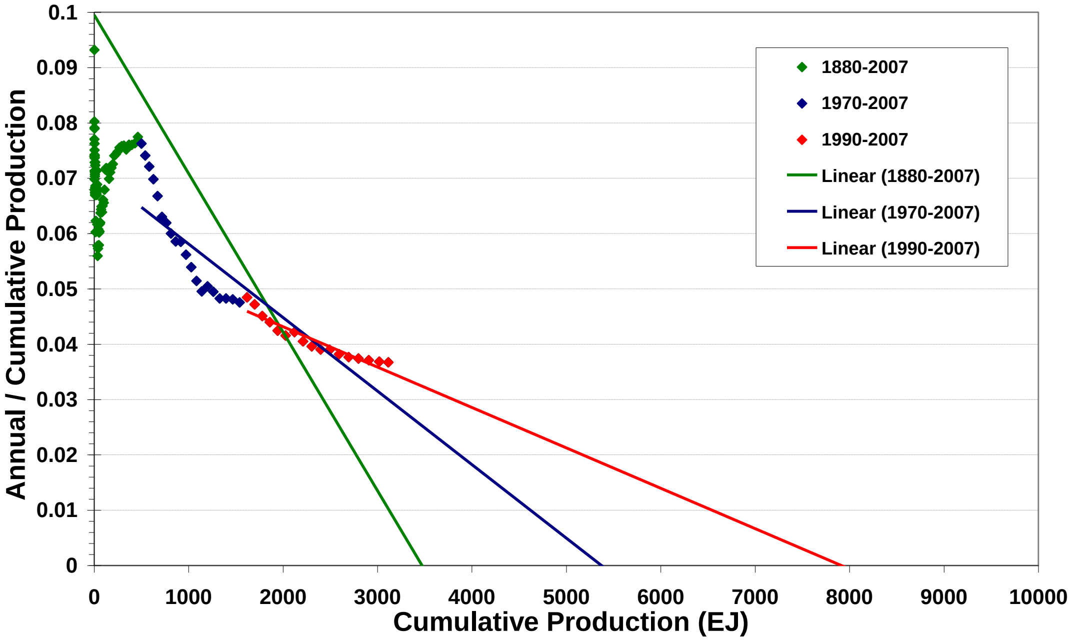


Figure D-5 Linearisation of conventional gas production in various periods

Looking at the rate of change of the logistic growth curves we see a remarkably close fit with the data for annual gas production. The curves for the periods 1880-2007, 1970-2007 and 1990-2007 predict peaks in gas production in 1998, 2004 and 2012 at 87, 97 and 111 EJ per year respectively. Again we see that IEA projections for the period to 2030 are much higher than these curves (IEA, 2008c).

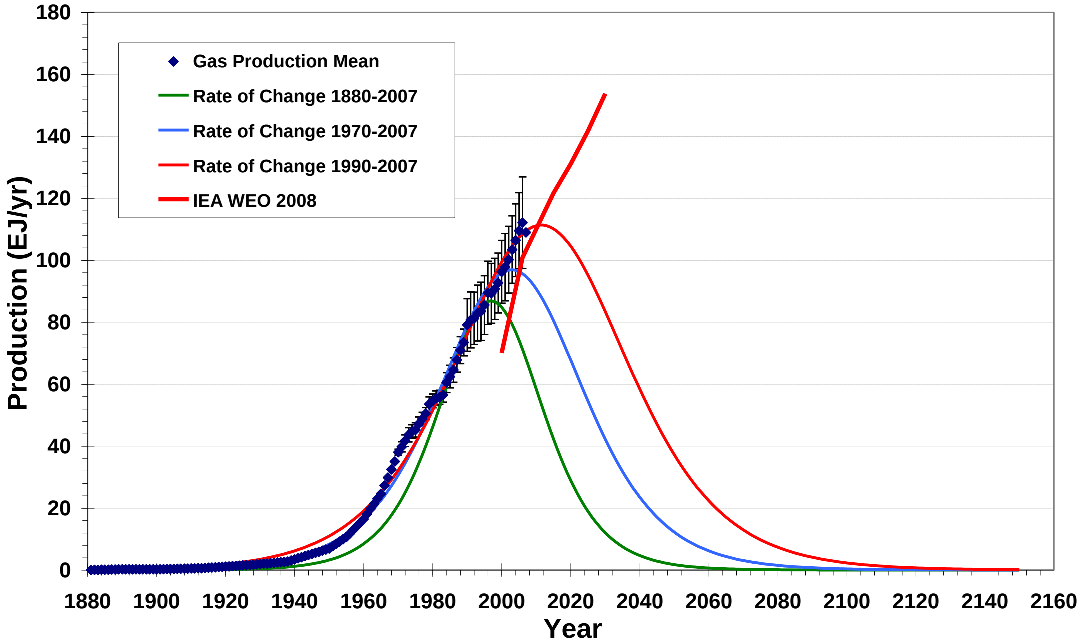


Figure D-6 Annual gas production compared with rate of change of logistic growth curves for various values of r and K

D.1.4 All Fossil Fuels:

Looking at the aggregation of the fossil fuels; coal, oil and gas, (see Figure D-7) we see a period of relative stability from 1970-2006 but, as with coal, the data swings away from this line due to the large increase in production in recent years.

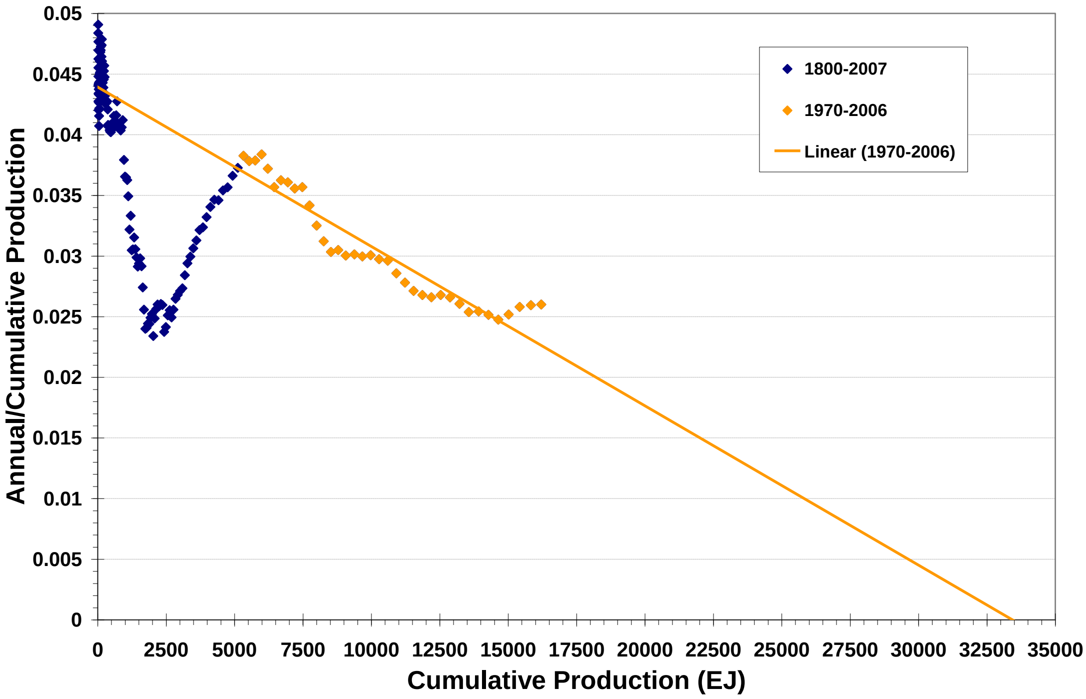


Figure D-7 Linearisation of all fossil fuel production: coal, conventional oil and conventional gas

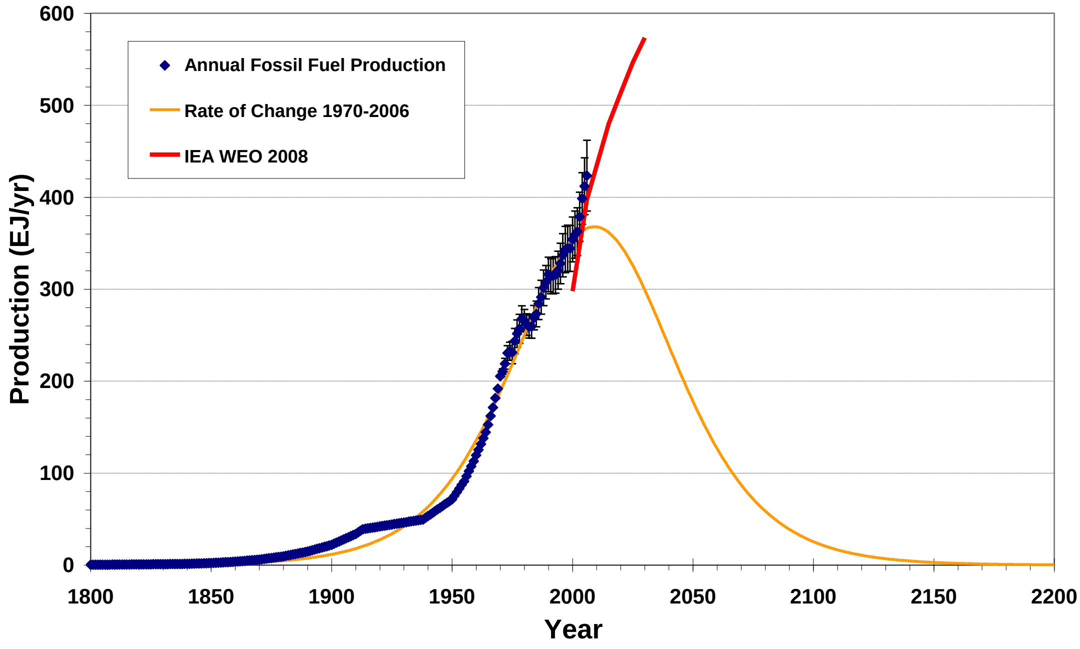


Figure D-8 Annual fossil fuel production compared with rate of change of logistic growth curve

D.1.5 Nuclear:

The linearisation curve for nuclear production (see Figure D-9) displays some distinct stable periods between 1985-1995 and again between 1995-2007. Again the value of K increases as the cumulative production increases.

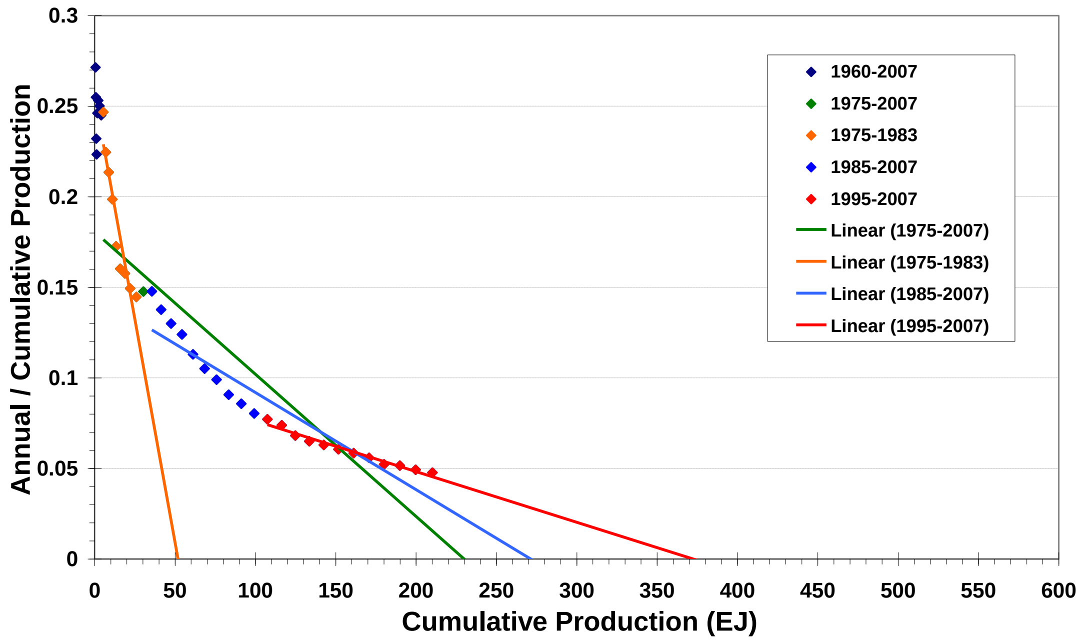


Figure D-9 Linearisation of nuclear energy production

Comparing the rate of change of the logistic growth curve with the data for nuclear energy production (see Figure D-10) we see that all of the curves underestimate present levels of production. The curves for the periods 1975-2007, 1985-2007 and 1995-2007 all have peaked in 1999, 2000 and 2003 at 10.3, 9.8 and 9.6 EJ per year respectively, again far lower than IEA projections for the period to 2030 (IEA, 2008c)[44].

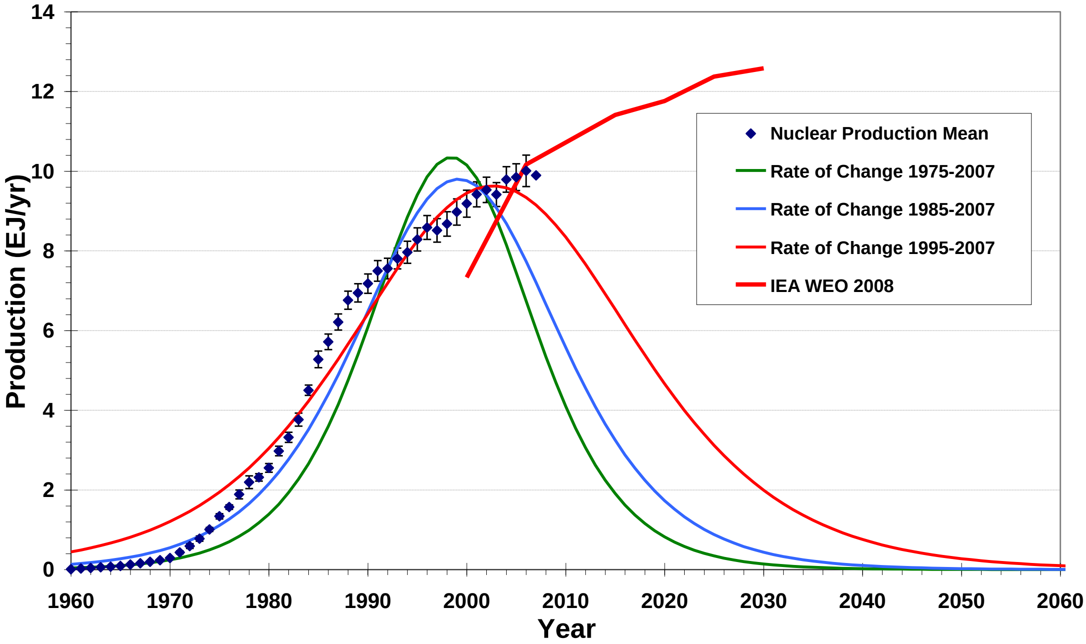


Figure D-10 Annual nuclear production compared with rate of change of logistic growth curves for various values of r and K

44 The figures for nuclear (electricity) production presented here are less than the IEA values by a factor of three, presumably to account for primary thermal energy normally expended in producing electricity, as most thermal power plants are around 33% efficient.

D.1.6 All Fissile and Fossil Fuels:

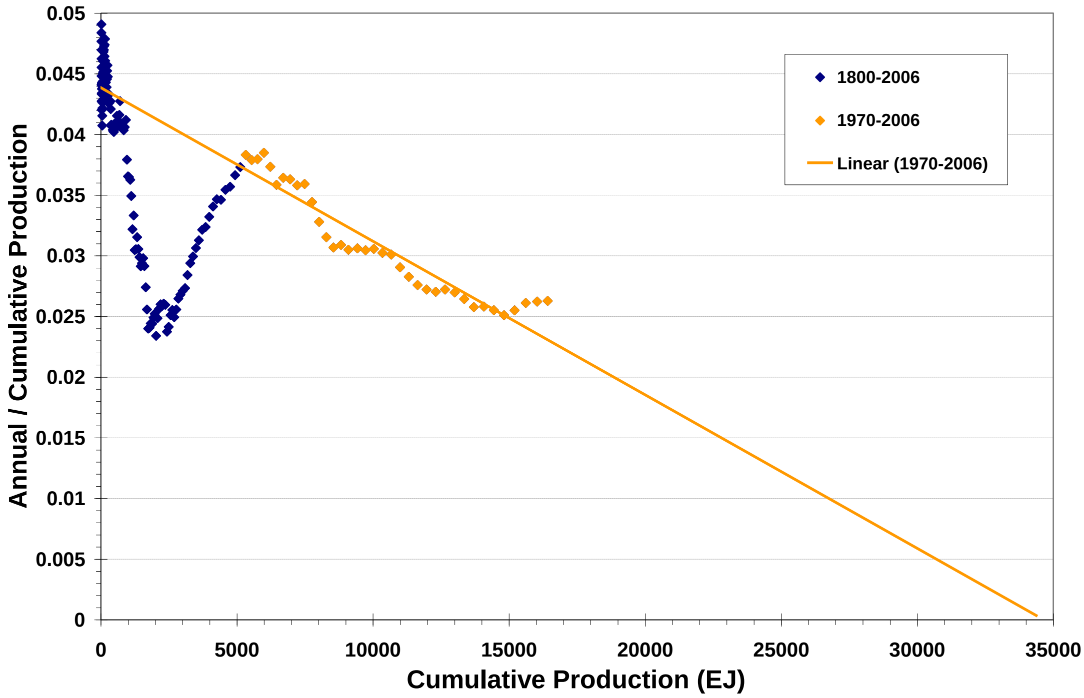


Figure D-11 Linearisation of all fissile and fossil fuel energy production

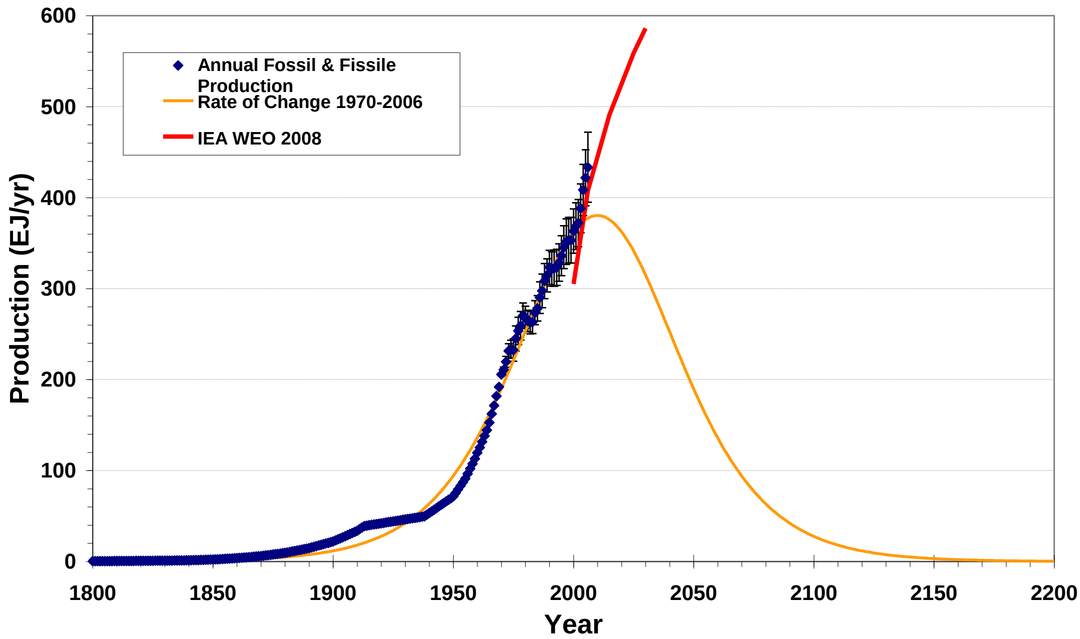


Figure D-12 Annual nuclear production compared with rate of change of logistic growth curve

D.1.7 Summary

Table D-1 'Best fit' values of r and K for various periods for all non-renewable energy sources

	r	K (EJ)	R^2
Coal			
1867-2007	0.0399	8000	0.66
1913-2007	0.0280	13500	0.44
1938-2000	0.0209	39300	0.51
1938-2007	0.0205	53400	0.40
Oil			
1860-2007	0.1182	6100	0.1
1965-2007	0.0739	8800	0.88
1985-2007	0.0478	14300	0.95
Gas			
1880-2007	0.0995	3500	0.81
1970-2007	0.0714	5400	0.84
1990-2007	0.0578	7500	0.89
Fossil Fuels			
1970-2006	0.0442	33300	0.90
Nuclear			
1975-2007	0.1800	230	0.83
1985-2007	0.1452	270	0.90
1995-2007	0.1041	370	0.97
Fossil & Fissile			
1970-2006	0.0441	34500	0.90

D.2 Fitting Logistic Growth Curves to Cumulative Production:

Another method for fitting the logistic growth curve to the historic data is to determine the values of *r* and *K* that minimise the residual sum of squares (called RSS on the graphs) between the logistic growth curve and cumulative production (see Table D-1). We can now see how well this technique allows us to fit the data.

Table D-2 'Best fit' values of r, K, and P_0 with associated value for RSS

	r	K (EJ)	P_0 (EJ)	t_0	R^2
Coal	0.0292	11844	33	1800	0.998
Oil	0.0708	8948	1	1860	1
Gas	0.0734	5070	0.7	1880	1
Fossil Fuels	0.0349	78596	256	1800	1
Nuclear	0.0811	9248	6	1960	0.98
Fossil & Fissile Fuels	0.0354	73465	15	1800	0.99

D.2.2 Coal:

As can be seen from the graph (see Figure D-13) the logistic curve fits the data for cumulative production very well, yielding a value for K of ~ 12000 EJ (around 400 Billion tonnes of coal[45]); however, when we look at the data for annual coal production (see Figure D-14) we see that this 'best fit' curve predicts a peak in production at around 90 EJ sometime near the year 2000. This is well below current production levels and IEA projections.

[45] This assumes an energy content of coal of 29 GJ/m^3

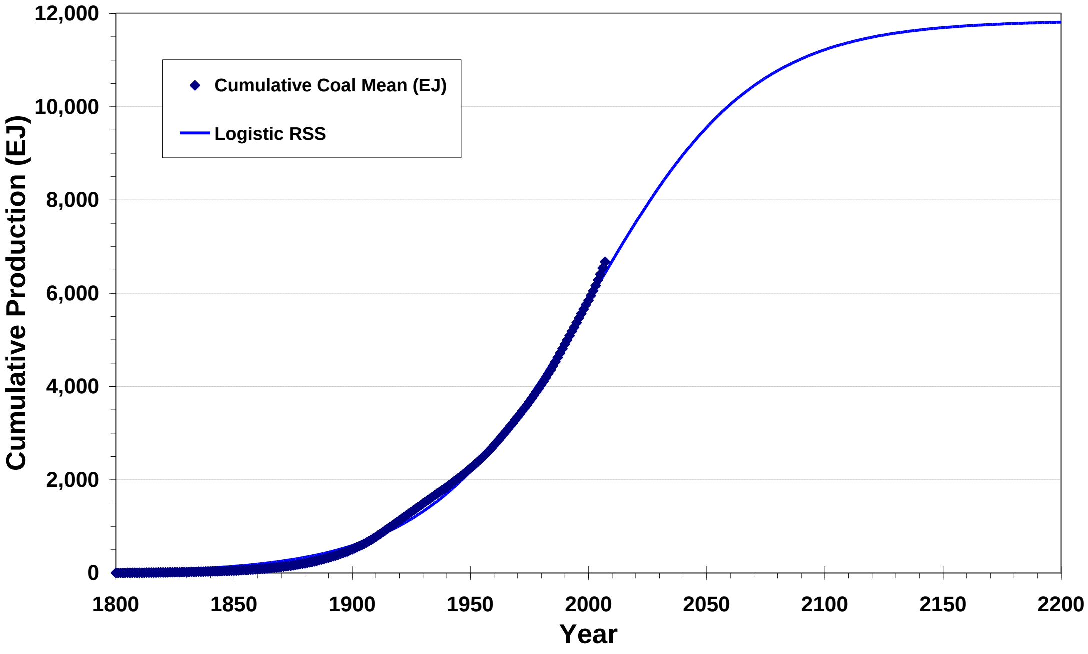


Figure D-13 Cumulative coal production with 'best-fit' logistic growth curves using RSS technique

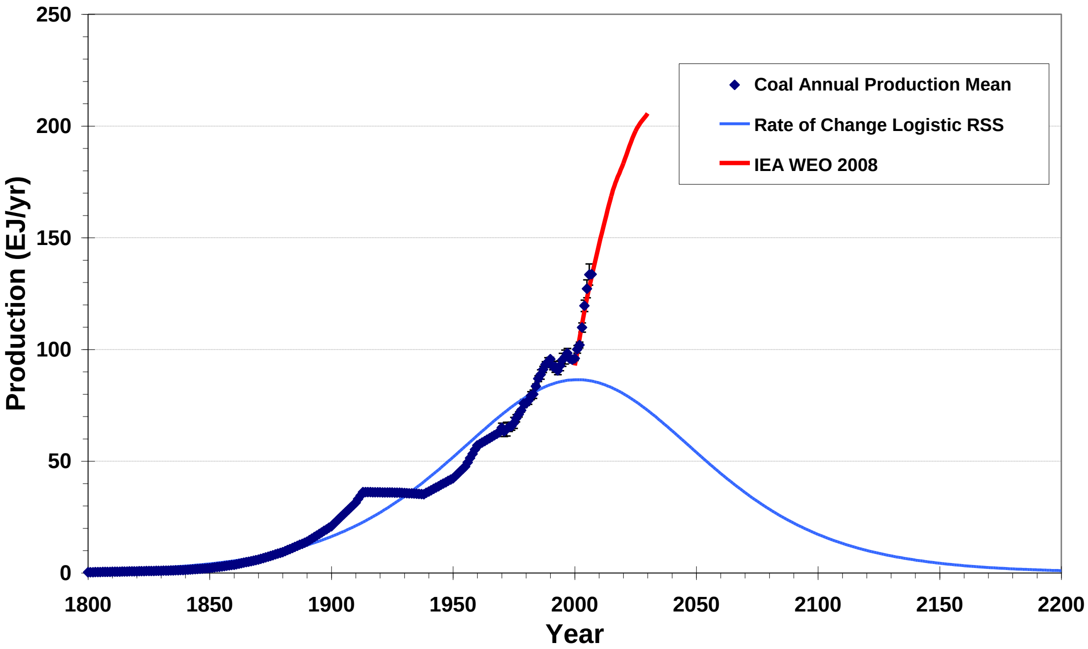


Figure D-14 Annual coal production with rate of change of 'best fit' logistic growth curve

D.2.3 Oil:

Again the logistic curve fits the cumulative production data very closely (see Figure D-15), but gives a very low value for K ~ 9000 EJ (equivalent to around 1450 Billion barrels[46]). This curve predicts a peak in oil production in 1993 at 158 EJ per year (see Figure D-16) far below both current production levels and IEA projections to 2030 (IEA, 2008c).

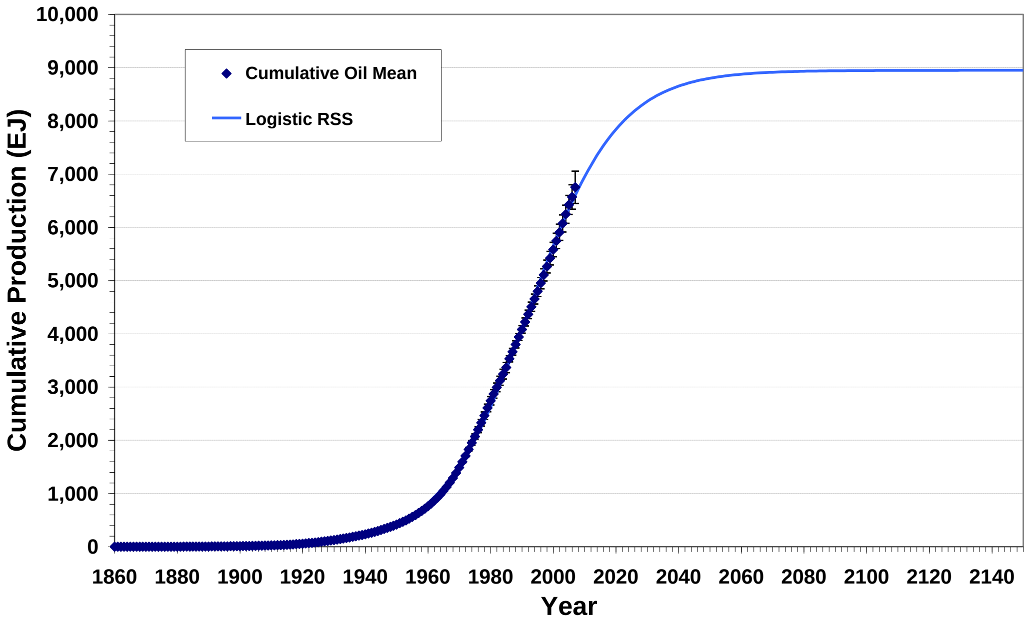


Figure D-15 Cumulative oil production with 'best-fit' logistic growth curves using RSS technique

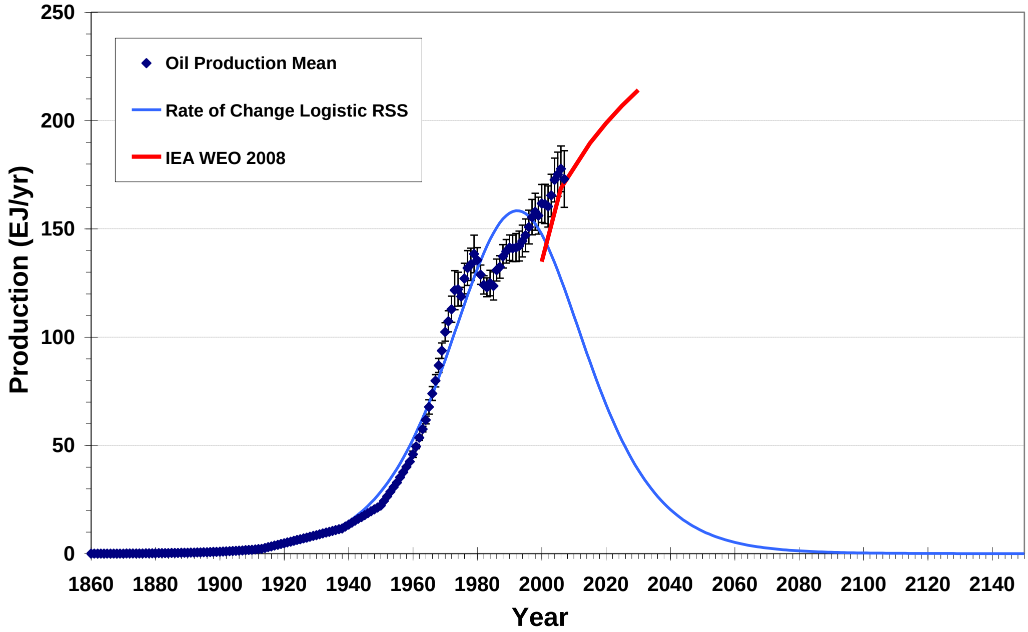


Figure D-16 Annual oil production with rate of change of 'best fit' logistic growth curve

[46] This figure assumes an energy content of 6.2 GJ per barrel of oil. The median value of estimates for ultimately recoverable reserves of conventional oil is 13,000 EJ equivalent to 2100 billion barrels (see CHAPTER 6)

D.2.4 Gas:

Looking at the plot (see Figure D-17) we can see a close fit between the cumulative gas production data and the logistic growth curve; however, again, the value of K is very low at ~ 5000 EJ (around 806 Billion barrels of oil equivalent or 130 Trillion cubic metres of gas[47]). This curve predicts a peak in gas production in the year 2000 at 93 EJ per year, again below current production levels and IEA projections.

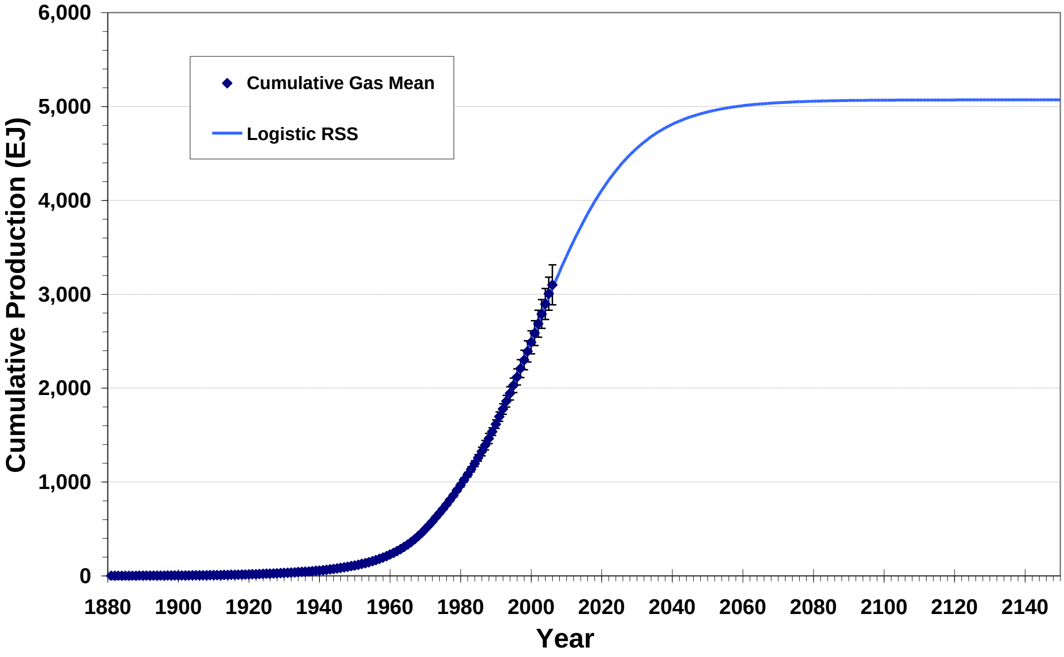


Figure D-17 Cumulative gas production with 'best-fit' logistic growth curves using RSS technique

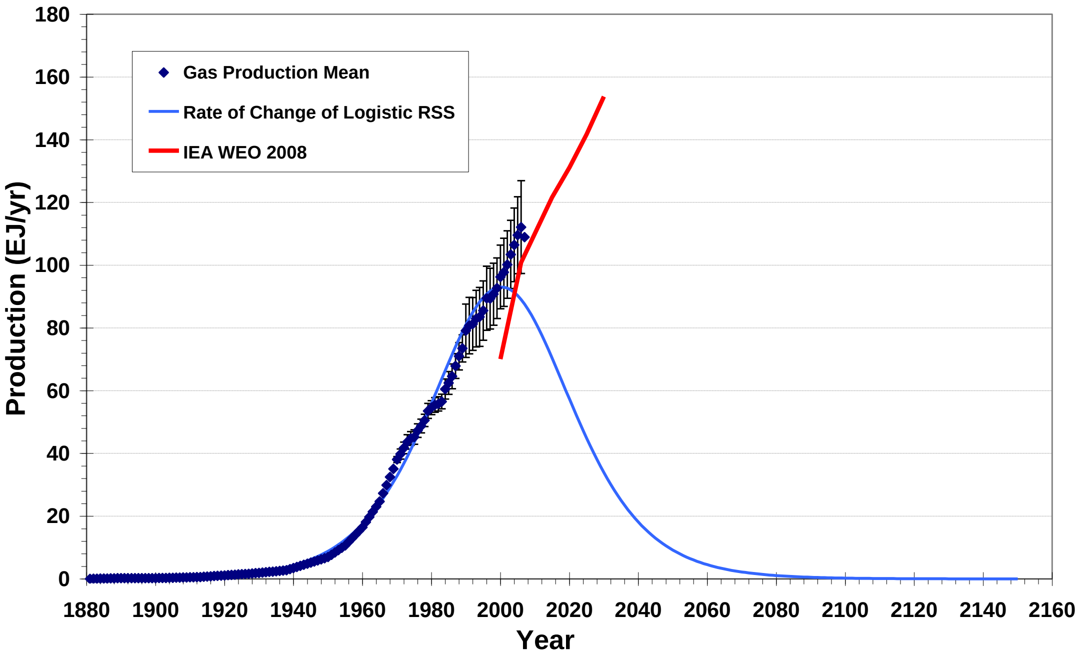


Figure D-18 Annual gas production with rate of change of 'best fit' logistic growth curve

[47] This assumes the energy content of gas is 39 MJ/m^3

D.2.5 All Fossil Fuels:

When aggregating all of the fossil fuels we see that, as well as the logistic curve closely fitting the data for cumulative production (see Figure D-19) the value obtained for K is much greater than the sum of the three fuels independently, at ~ 78000 EJ (around 12600 Billion barrels of oil equivalent). This curve predicts a peak in fossil fuel production in 2045 at around 690 EJ per year, which encompasses both current production and IEA projections to 2030 (see Figure D-20).

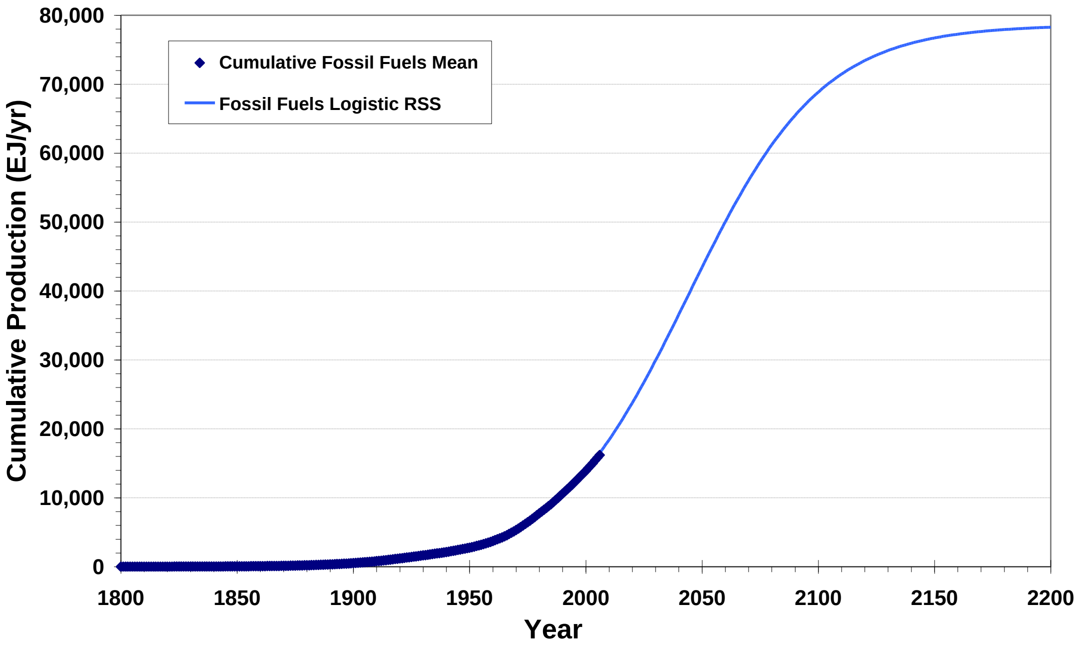


Figure D-19 Cumulative fossil fuel production with 'best-fit' logistic growth curves using RSS technique

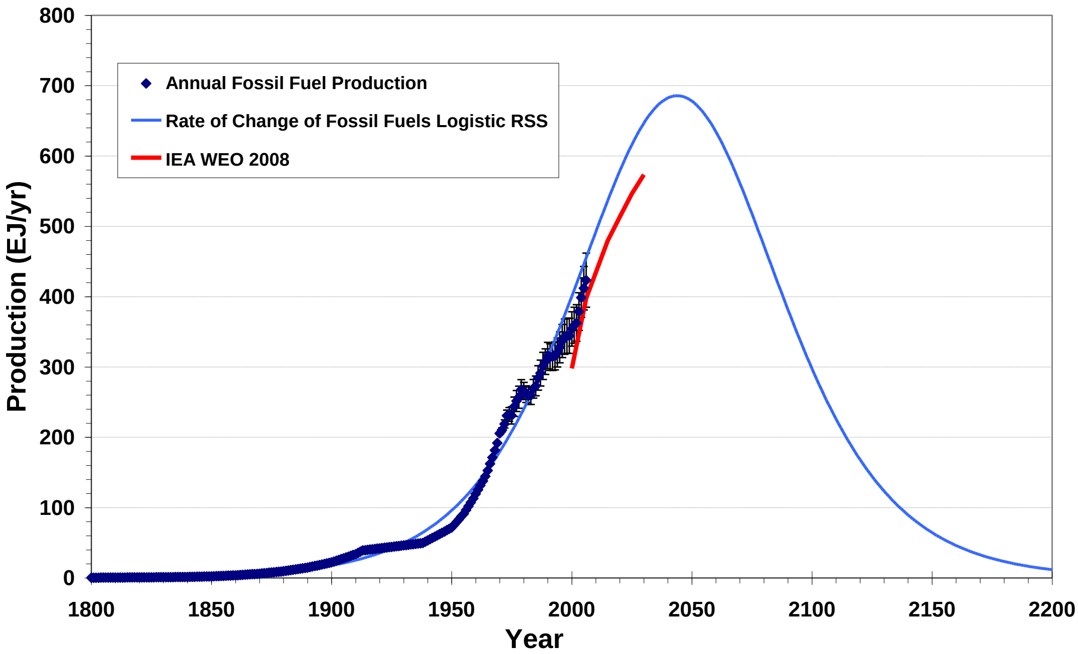


Figure D-20 Annual fossil fuel production with rate of change of 'best fit' logistic growth curve

D.2.6 Nuclear:

Looking at the plot for cumulative nuclear production (see Figure D-21) we see a close fit between the logistic growth curve and the data. The value obtained for K is ~ 9200 EJ (equivalent to 56 Million tonnes of natural uranium, assuming a requirement of 22 tonnes of natural uranium to produce each TWh of electricity (UNDP, 2000)[48]), using this curve predicts a peak in production in 2052 at around 190 EJ per year, greatly higher than current production and IEA projections (see Figure D-22).

---

[48] This figure for the uranium resource is orders of magnitude greater than current estimates of the global endowment of uranium resource (see CHAPTER 6) , however this estimate is based on uranium requirements of burner technology. Breeder reactors, with a lower requirement on natural uranium may be able to achieve a total output of somewhere in the region of 9000 EJ.

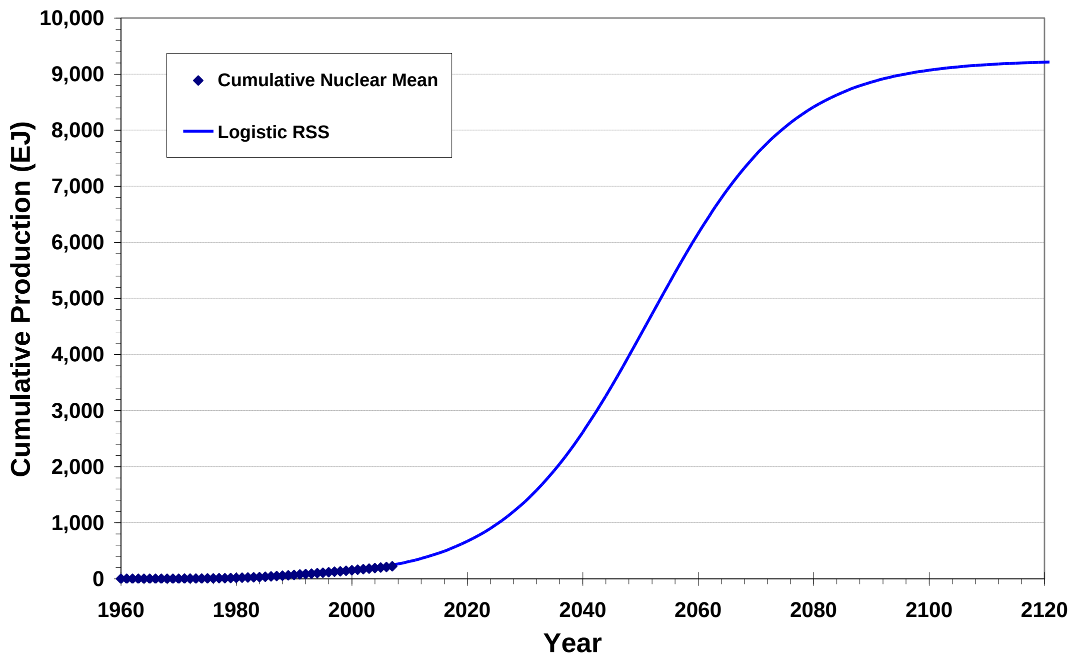


Figure D-21 Cumulative nuclear production with 'best-fit' logistic growth curves using RSS technique

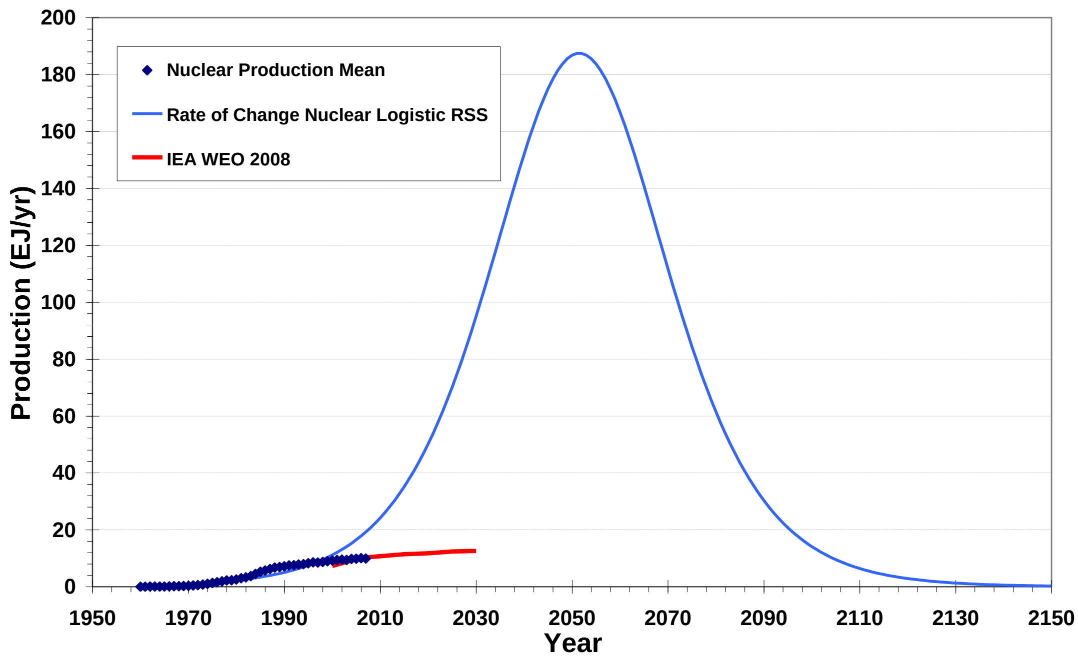


Figure D-22 Annual nuclear production with rate of change of 'best fit' logistic growth curve

D.2.7 All Fossil & Fissile Fuels:

If we again aggregate all of the fossil fuels and include nuclear too we can see the logistic growth curve closely matches the data for cumulative production (see Figure D-23, although the value of K obtained in this case, ~ 73,000 EJ (around 11800 Billion barrels of oil equivalent), is less than that for just the fossil fuels[49]. This curve yields a peak in production around 2040 at 650 EJ per year, marginally greater than current production and IEA projections (IEA, 2008c).

[49] This is probably due to nuclear production having been somewhat slow since the late eighties, acting to 'slow' the growth of the aggregated fossil and fissile products, resulting in a lower value of K

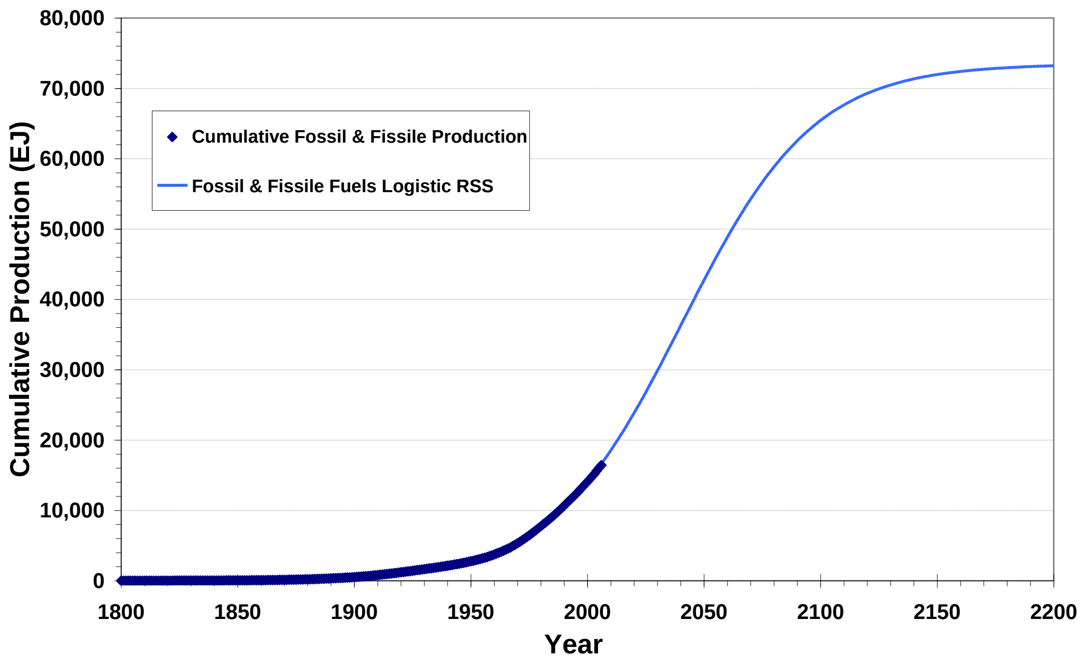


Figure D-23 Cumulative fossil and fissile fuels production with 'best-fit' logistic growth curve using RSS technique

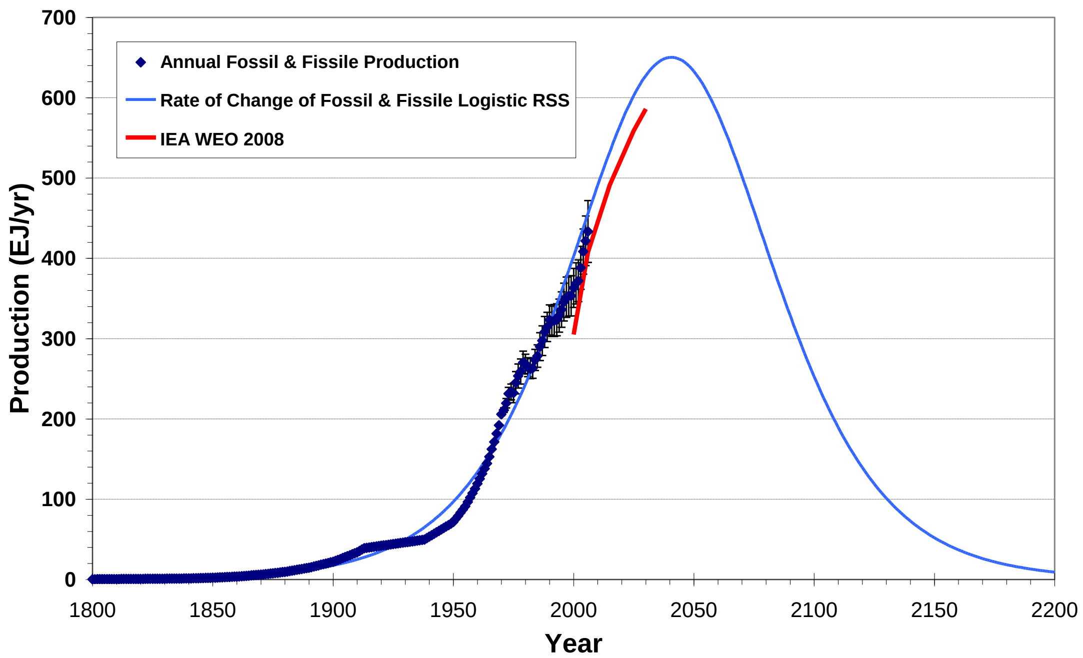


Figure D-24 Annual fossil and fissile fuel production with rate of change of 'best fit' logistic growth curve

D.3 Fitting Logistic Curves to Annual Production:

We can also make use of the RSS technique to fit the curve describing the rate of change of the logistic growth curve to the data for annual production of each of the fuels. We can also find the best fit curve for the IEA projections and see what each of these entails for values of K.

Table D-3 Parameters of 'best fit' of logistic curve to annual energy production

	r	K (EJ)	P_0 (EJ)	t_0	R^2
Coal					
Historic data	0.0200	48,263	128	1800	0.98
IEA projections	0.0330	30,000	7	1800	0.92
Historic + IEA[50]	0.0200	187,092	115	1800	0.97
Oil					
Historic data	0.0589	11,069	3	1860	0.98
IEA projections	0.0292	29,954	26	1860	0.95
Historic + IEA	0.0348	24,767	7	1860	0.96
Gas					
Historic data	0.0619	6894	2	1880	0.995
IEA projections	0.0170	146,652	208	1880	0.93
Historic + IEA	0.0469	11,994	0.3	1880	0.99
Fossil Fuels					
Historic data	0.0416	39,385	138	1800	0.99
IEA projections	0.0489	45,495	0.6	1800	0.95
Historic + IEA	0.0346	66,143	17	1800	0.99
Nuclear					
Historic data	0.0516	9248	22	1960	0.89
IEA projections	0.0126	9296	527	1960	0.96
Historic + IEA	0.0642	772	16	1960	0.95
Fossil & Fissile Fuels					
Historic data	0.0419	40,395	5	1800	0.99
IEA projections	0.0251	108,368	145	1800	0.97
Historic + IEA	0.0346	66,143	17	1800	0.99

[50] In this case the 'best fit' curve was constrained by having to pass through both the first and last years of IEA projections (2008 and 2030). If this constraint was removed the value of K obtained was of the order of 10^{12} EJ.

D.3.2 Coal:

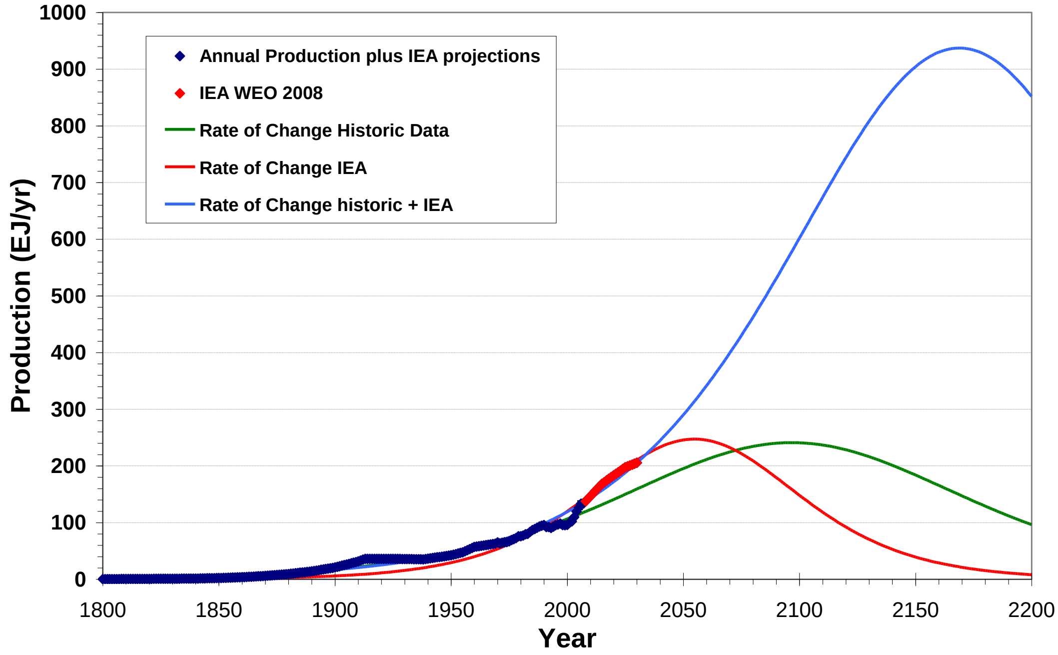


Figure D-25 Annual coal production with rate of change of 'best fit' logistic growth curve using RSS technique

D.3.3 Oil:

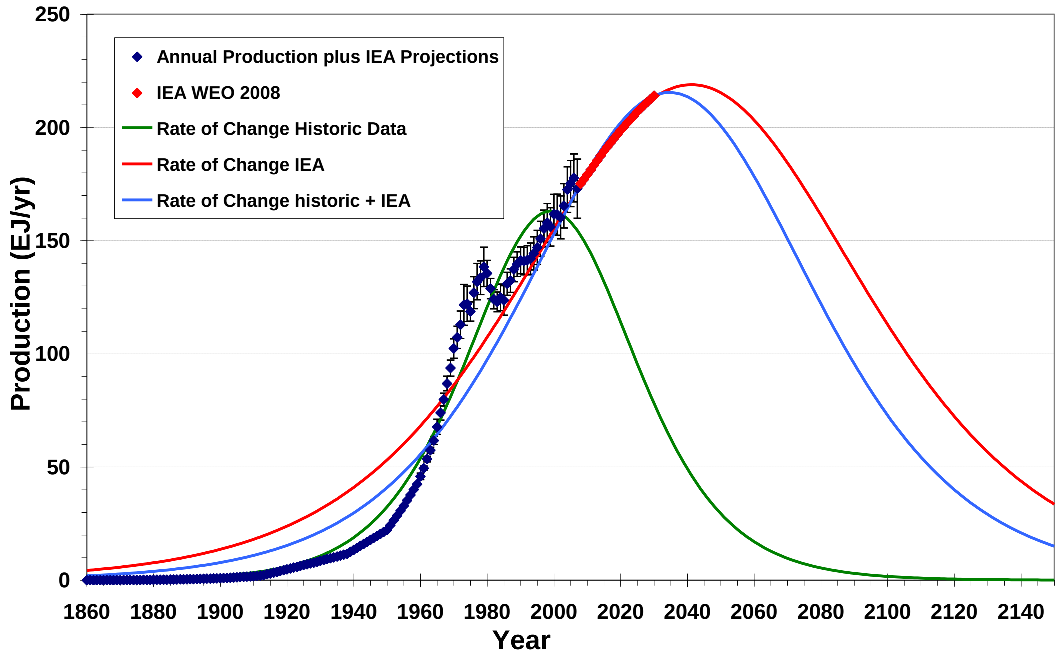


Figure D-26 Annual oil production with rate of change of 'best fit' logistic growth curve using RSS technique

D.3.4 Gas:

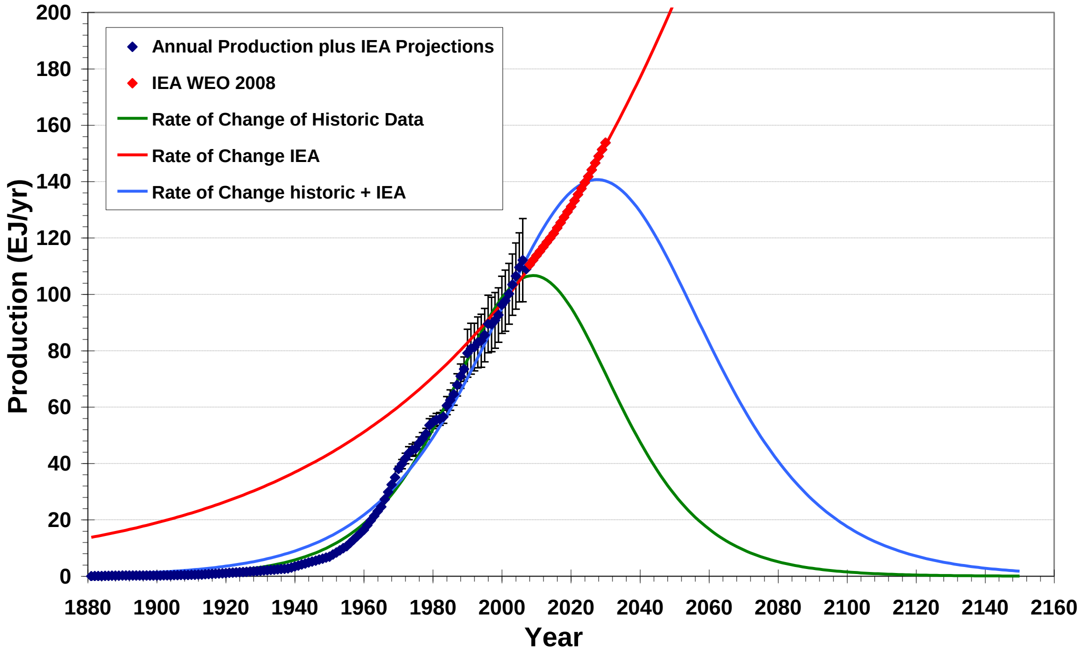


Figure D-27 Annual gas production with rate of change of 'best fit' logistic growth curve using RSS technique

D.3.5 Fossil Fuels:

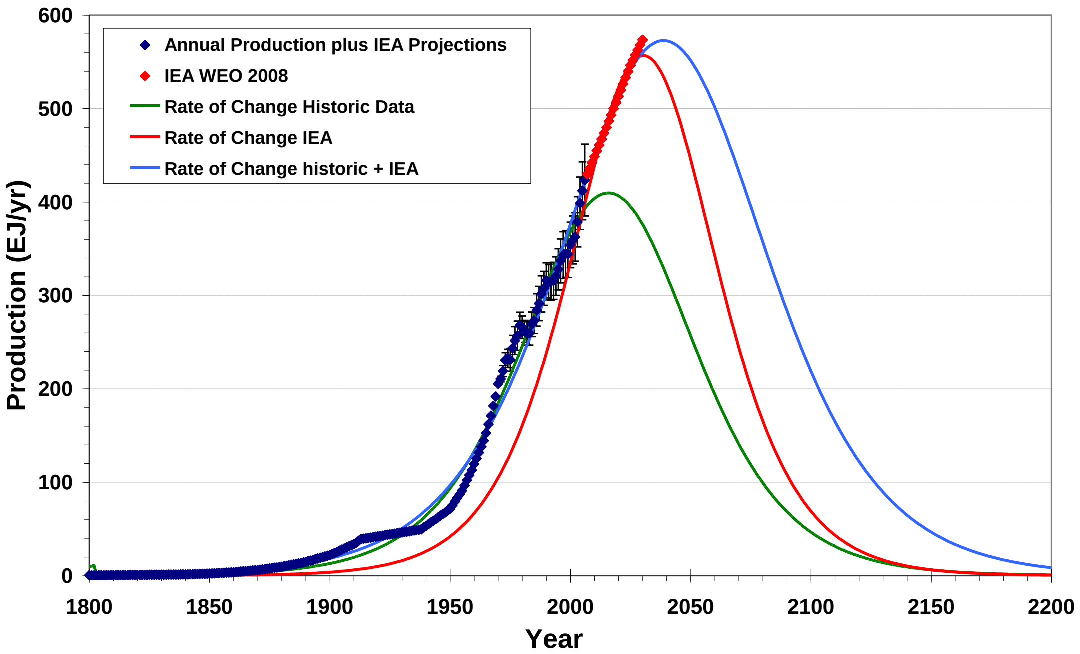


Figure D-28 Annual fossil fuel production with rate of change of 'best fit' logistic growth curve using RSS technique

D.3.6 Nuclear:

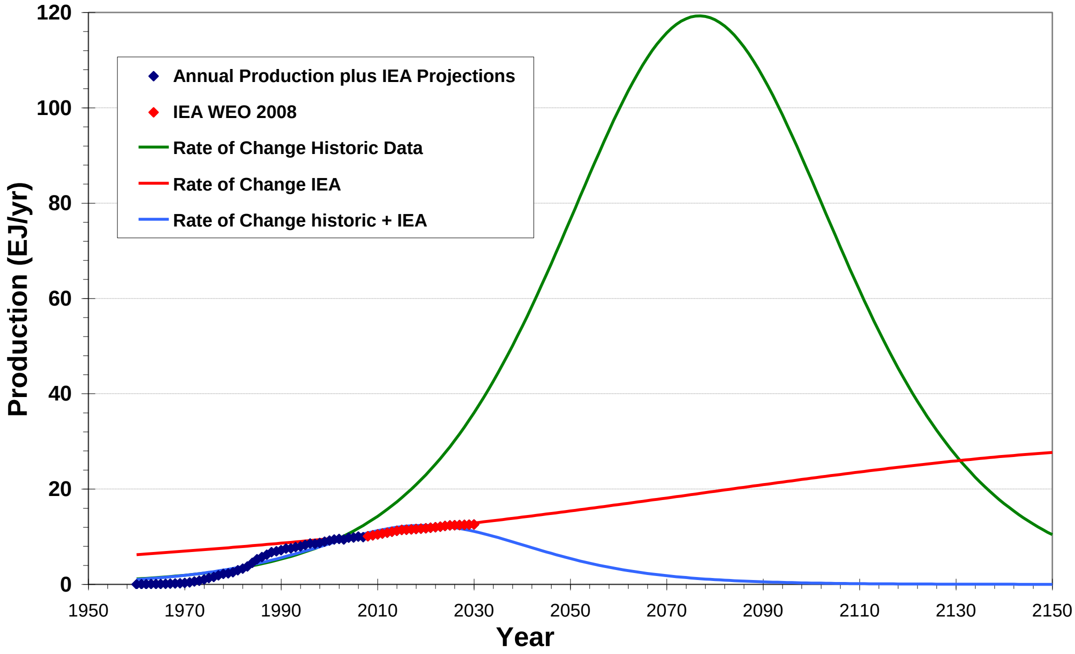


Figure D-29 Annual gas production with rate of change of 'best fit' logistic growth curve using RSS technique

D.3.7 Fossil & Fissile Fuels:

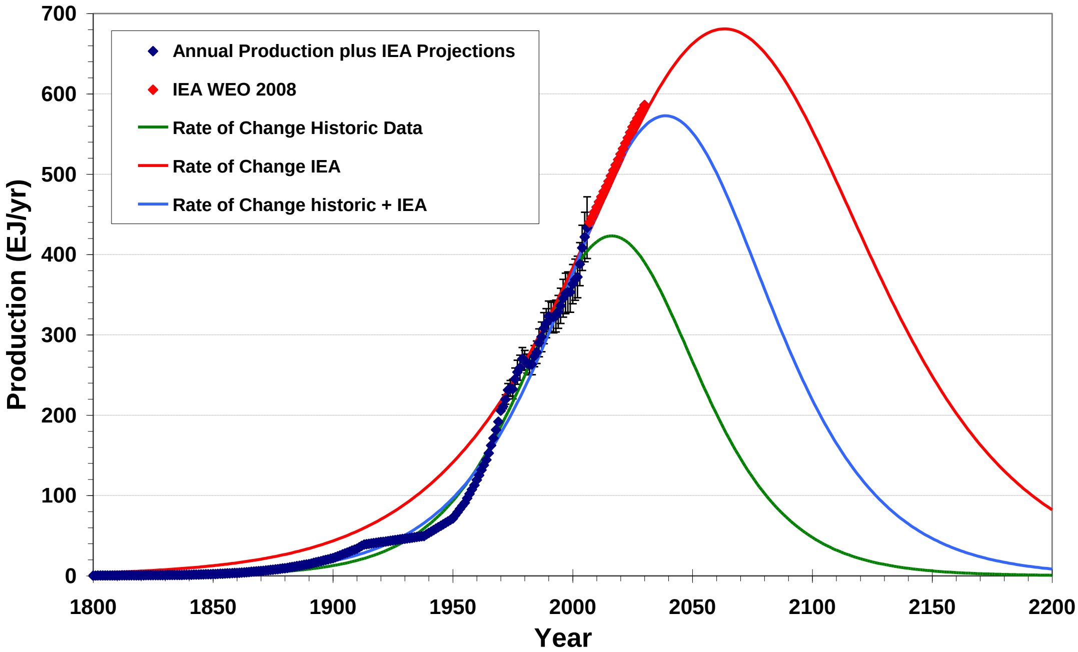


Figure D-30 Annual fossil and fissile fuel production with rate of change of 'best fit' logistic growth curve using RSS technique

D.4 Summary:

As can be seen from the preceding analysis the use of modelling production data with a logistic growth curve by no means guarantees a convergence in the values obtained for either r or K. In many cases the range of values for r, K and P_0 is greater than the mean of those values.

An interesting point of note is that a large change in the value of K does not necessarily correspond to a large change in the predicted peak of production. This is especially noteworthy of the oil production scenarios wherein the value of K varies by a factor of nearly *five* and yet the range of the peak years is only 50 years. This observation leads me to reflect on the IEA projections for the period to 2030 wherein they show ever increasing production. It may well be that we are able to supply this demand to this date with existing resources but two questions immediately spring to mind: "to what end?" and, "what then?"

Table D-4 Summary of logistic growth curves under various scenarios

	r	K (EJ)	P_0 (EJ)	t_0	Peak Year	Peak Production (EJ/yr)
Coal						
Linear Regression						
1867-2007	0.0399	8000	4	1800	1990	80
1913-2007	0.0280	13500	37	1800	2010	95
1938-2000	0.0209	39300	109	1800	2081	205
1938-2007	0.0205	53400	111	1800	2101	274
Fit Cumulative Production	0.0292	11844	33	1800	2001	86
Fit Annual Production						
Historic data	0.0200	48263	128	1800	2097	241
IEA projections	0.0330	30000	7	1800	2055	247
Historic + IEA[51]	0.0200	187092	115	1800	2169	937
MEAN	0.0264	48925	68	1800	2063	271
RANGE	0.0199	179092	124	0	179	857

[51] In this case the 'best fit' curve was constrained by having to pass through both the first and last years of IEA projections (2008 and 2030). If this constraint was removed the value of K obtained was of the order of 10^{12} EJ.

	r	K (EJ)	P_0 (EJ)	t_0	Peak Year	Peak Production (EJ/yr)
Oil						
Linear Regression						
1860-2007	0.1182	6100	1E-3	1860	1991	180
1965-2007	0.0739	8800	0.4	1860	1994	163
1985-2007	0.0478	14300	12	1860	2008	171
Fit Cumulative Production	0.0707	8950	0.8	1860	1992	158
Fit Annual Production						
Historic data	0.0589	11069	3	1860	1999	163
IEA projections	0.0292	29954	26	1860	2041	219
Historic + IEA[52]	0.0348	24767	7	1860	2035	215
MEAN	0.0619	14849	7	1860	2008	181
RANGE	0.0890	23854	26	0	50	61
Gas						
Linear Regression						
1880-2007	0.0993	3500	0.03	1880	1997	87
1970-2007	0.0718	5400	0.8	1880	2003	97
1990-2007	0.0594	7500	3	1880	2011	111
Fit Cumulative Production	0.0734	5070	0.7	1880	2000	93
Fit Annual Production						
Historic data	0.0619	6894	2	1880	2009	107
IEA projections	0.0170	146652	208	1880	2186	622
Historic + IEA	0.0469	11994	0.3	1880	2028	141
MEAN	0.0614	26716	31	1880	2033	180
RANGE	0.0823	143152	208	0	189	535

[52] In this case the 'best fit' curve was constrained by having to pass through both the first and last years of IEA projections (2008 and 2030). If this constraint was removed the value of K obtained was of the order of 10^{12} EJ.

	r	K (EJ)	P_0 (EJ)	t_0	Peak Year	Peak Production (EJ/yr)
All Fossil Fuels						
Linear Regression						
1970-2006	0.0442	33300	3	1800	2009	369
Fit Cumulative Production	0.0349	78596	256	1800	2044	686
Fit Annual Production						
Historic data	0.0416	39385	138	1800	2016	410
IEA projections	0.0489	45495	0.6	1800	2030	557
Historic + IEA	0.0346	66143	17	1800	2039	573
MEAN	0.0408	52584	83	1800	2028	519
RANGE	0.0143	45296	255	0	35	317
Nuclear						
Linear Regression						
1975-2007	0.1800	230	0.2	1960	1998	10
1985-2007	0.1452	270	0.9	1960	1999	10
1995-2007	0.1041	370	4	1960	2003	10
Fit Cumulative Production	0.0811	9248	6	1960	2051	187
Fit Annual Production						
Historic data	0.0516	9248	22	1960	2077	119
IEA projections	0.0126	9296	527	1960	2183	29
Historic + IEA	0.0642	772	16	1960	2019	12
MEAN	0.0913	4205	82.3	1960	2047.14286	54
RANGE	0.1674	9066	526.8	0	185	177
All Fossil & Fissile						
Linear Regression						
1970-2006	0.0441	34500	3	1800	2010	380
Fit Cumulative Production	0.0354	73465	15	1800	2041	650
Fit Annual Production						
Historic data	0.0419	40395	5	1800	2016	423
IEA projections	0.0251	108368	145	1800	2063	681
Historic + IEA	0.0346	66143	17	1800	2039	573
MEAN	0.0362	64574	37	1800	2034	541
RANGE	0.0190	73868	142	0	53	301